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ARMSED, A RUNOFF AND SEDIMENT YIELD MODEL FOR ARMY TRAINING LAND WATERSHED MANAGEMENT VOLUME I: PARAMETER ESTIMATION GUIDE

by
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Army land managers and environmental planners must estimate runoff and sediment yield from small, ungaged watersheds on Army training lands to assess the condition of the lands and to evaluate alternative erosion control plans. The U.S. Army Construction Engineering Research Laboratory (USACERL) developed the Army multiple watershed storm water and sediment runoff (ARMSED) simulation model, which is based on the MULTSED model and has been adapted for Army use.

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FOREWORD

This research was conducted for the U.S. Army Engineering and Housing Support Center (USAEHSC) under Project 4A162720A896, "Environmental Quality Technology"; Technical Area A, "Installation Environmental Management"; Work Unit 097, "Physical/Structural Erosion Control for Training Land Rehabilitation." The USAEHSC Technical Monitor was Donald Bandel, CEHSC-FN.

The work was accomplished by the Environmental Division (EN) of the U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. Timothy Ward is Professor of Civil Engineering at New Mexico State University. Dr. R. K. Jain is Chief of EN. The Technical Editor was Gloria J. Wienke, Information Management Office.

COL Carl O. Magnell is Commander and Director of USACERL and Dr. L. R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

Army land managers and environmental planners must estimate runoff and sediment yield from small, ungaged watersheds on Army training lands. These estimates are needed to help assess the condition of the lands and to evaluate alternative erosion control plans. Because estimating runoff and sediment yield is a difficult hydrologic task, mathematical computer models can be an important part of the process. The U.S. Army Construction Engineering Research Laboratory (USACERL) developed the Army multiple watershed storm water and sediment runoff (ARMSED) simulation model, which is based on the MULTSED model developed at Colorado State University. USACERL conducted studies of MULTSED to test the formulation and sensitivity of the model.[1] ARMSED is an Army tailored adaptation of MULTSED.

ARMSED is a single event, distributed, deterministic simulation model that operates on MS-DOS compatible microcomputers with 512K RAM. A 10-megabyte hard disk is recommended.

Objective

This report provides documentation and guidance to ARMSED users. Volume I is a guide for selecting and estimating the various input parameters and values required to operate the model. The program structure is documented in Volume II.

Approach

The guide is divided into sections based on the general type of input required, such as geometry, soils, and vegetation. A brief explanation of the type of information is given. Specific input variables are discussed in more detail, and methods of parameter selection are presented. As an additional aid to the user, default values for the data are provided. The guide includes an example of model application.

Because ARMSED is based on physical processes, parameters can be derived from field measurements. Standard methods for field data collection using a portable rainfall simulator are presented in the Appendix.

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[1]H. G. Wenzel, Jr. and C. S. Melching, *An Evaluation of the MULTSED Simulation Model to Predict Sediment Yield*, Technical Report N-87/27/ADA185615 (U.S. Army Construction Engineering Research Laboratory [USACERL], September 1987).

Mode of Technology Transfer

The ARMSED program is available on a 5¼-in. floppy disk and can be obtained by contacting Mr. Robert E. Riggins at USACERL-EN, P. O. Box 4005, Champaign, IL 61820-1305. Telephone: commercial 217/373-7234, or toll-free 800/USA-CERL (outside Illinois), 800/252-7122 (within Illinois). ARMSED will be fielded under the Integrated Training Area Management Program as part of the Maintenance and Scheduling Support System. As the user base expands, the model will be updated and modified to incorporate new data and ideas.

2 MODEL INPUTS

ARMSED requires data on geometric characteristics, soil characteristics, surface characteristics, rainfall characteristics, and miscellaneous inputs. The input parameters and input format are listed in Volume II.

Geometric Characteristics

Because most watersheds are nonhomogeneous in topography, soils, vegetation, and other features, it is necessary to subdivide each watershed into units that can be treated as approximately homogeneous. Similarly, the channel system in a watershed can be represented by one or more segments, each having a characteristic location, shape, slope, and roughness. Table 1 lists the geometric parameters. The location, area, length, and slope of each watershed unit is usually obtained from topographic maps.

For the first submodel in the ARMSED model, MSED1, the watershed is subdivided into upland subwatershed units and plane units. These units flow into a third type of unit, the channel unit, which is treated in the third submodel, MSED3. A subwatershed is one that is situated at the uppermost portion of the drainage basin being modeled. A large drainage basin may have several subwatersheds, plane units, and channel units. As a minimum, there must be one plane representing the area being modeled. A plane is defined as a surface that drains into a channel.

Dividing the watershed into units is important for several reasons. First, the area of the unit determines, in part, the amount of runoff volume. Second, overland flow length and slope determine the rate at which water reaches channels. Third, the channel length, slope, and cross-sectional properties determine the rate at which water reaches the drainage basin outlet.

Watershed Geometry

The method presented below for subdividing an area is applicable to single subwatersheds or drainage basins of more complex geometry.

1. Obtain topographic and other maps of the drainage basin showing the important drainage features such as channels, channel junctions, soil types, and vegetation distribution.

2. Subdivide the drainage basin using one of the following criteria:

    a. Primary method. The drainage basin may be divided using the channel system. This division is often at the user's discretion but should be based on homogeneity in the channel segment or its contributing side slopes. This homogeneity may be the channel segment gradient or similar soil types on the contributing side slopes.

    b. Secondary method. The drainage basin may be divided into units that can be considered homogeneous by using the available topographic, soil type, and vegetation type maps for the watershed. The size of the division is based on the resolution needed and the availability of data.

Table 1

Geometric Parameters

ARMSED Variable	Unit	MSED Submodel	Description
PLENGTH	ft	1	Length of overland flow planes tributary to channels
SLOPE	decimal fraction	1	Slope of overland flow planes tributary to channels
LENGTH or SLEN	ft	1 3	Channel length
SLOPE or SLOP	decimal fraction	1 3	Channel slope
A1		1	Coefficient in channel wetted perimeter-flow area relationship
B1	--	1	Exponent in channel wetted perimeter-flow area relationship
A2	--	1,3	Coefficient in channel top width-flow area relationship
B2	--	1,3	Exponent in channel top width-flow area relationship

3. For each subwatershed, delineate the main channel in the unit. Extend the channel to the basin boundary by following the Vs of the contour lines or by crossing the contour lines perpendicularly. The extension must perpendicularly cross the contour elevations to ensure that the water is following the shortest path to the channel. Generally, a subwatershed should be smaller than 100 acres*. Watersheds larger than 100 acres should be subdivided into smaller units if possible.

4. Measure the length of the channel segment (PLENGTH).

5. Sketch in the boundaries between side slopes that contribute to different channel segments. The enclosed contributing areas are defined as the planes. Each channel has a left and right plane when looking downstream.

6. After all units of the basin are delineated, number the subwatersheds, channels, and planes. Although the numbers of the plane and channel units do not have to be in any particular order, it is strongly suggested that the units be numbered as follows:

a. Start subwatershed numbering using 1 for the first subwatershed encountered when moving counter-clockwise around the basin perimeter. Subwatersheds not located on the basin perimeter should also be numbered in a counter-clockwise pattern.

b. Start channel numbering at the most upstream channel. Number down the channel until the first tributary junction. If the junction is with a channel unit and not a subwatershed unit, then go to the most upstream unit of that channel and resume numbering in the downstream direction.

c. Start plane numbering with the first plane being the one contributing to channel 1 from the left hand side of the channel (when you are looking downstream). Examples of the numbering scheme are presented in Chapter 3.

7. Determine the slope of the channel (SLOPE) as the ratio of elevation difference at the channel end points to the channel length.

8. Determine the areas of the left and right contributing planes, using the channel as the dividing line.

9. Determine the overland flow length (PLENGTH) of each plane as the area of the plane divided by the channel length as determined in Step 4.

10. Locate approximately 5 to 20 sampling points. It is recommended that each point coincide with a contour line, when possible. At each sampling point, sketch out sampling lines from the channel to the subwatershed or plane unit boundary. Sampling lines are drawn perpendicular to contour lines and show the potential routes water would follow when flowing across the plane.

11. Sum the lengths of all the sampling lines on the plane. Similarly sum all the changes in elevations along the lines by adding all the starting elevations of the sampling lines, adding all the ending elevations, then subtracting the sum of the starting elevations from the sum of the ending elevations.

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*Metric conversion table is on page 49.

12. Determine the average slope (SLOPE) using the following:

$$S = \frac{Ht}{(Lt)} \qquad \text{[Eq 1]}$$

where S = the average overland slope
Ht = the difference between the sums of the beginning and ending elevations
Lt = the sum of all the sampling line lengths.

The following example shows how to use this procedure based on Figure 1.

Example 1: Determining areas, flow lengths, and slopes.

Area = 4.01 acres

Length of channel to watershed boundary = 632 ft

Change in channel elevation = 50 ft

Channel slope = 50/632 = 0.112

Side	Area (acres)	Plane width (ft)	Total Length of Sample Lines (ft)	Changes in Sample Line Elevations (ft)	Slope
Left	2.64	182.6	1387.0	125.0	0.090
Right	1.37	95.1	677.1	80.5	0.119

Channel Geometry

Another geometric measure of the watershed is the cross-sectional relationships of the stream channel. These relationships are used in the water and sediment routing models and relate the wetted perimeter to water flow area and top width to water flow area. The first relationship indicates the amount of land surface coming in contact with the flow and is thus used to determine flow resistance. The second relationship is used to determine other flow properties. In general, the procedure requires measurements on one or more cross sections in a channel and development of equations of the following form:

$$p = a1\ A^{b1} \quad \text{and} \quad T = a2\ A^{b2} \qquad \text{[Eq 2]}$$

where p = the wetted perimeter
T = top width
A = flow area
a1, a2, b1, and b2 = empirically determined parameters.

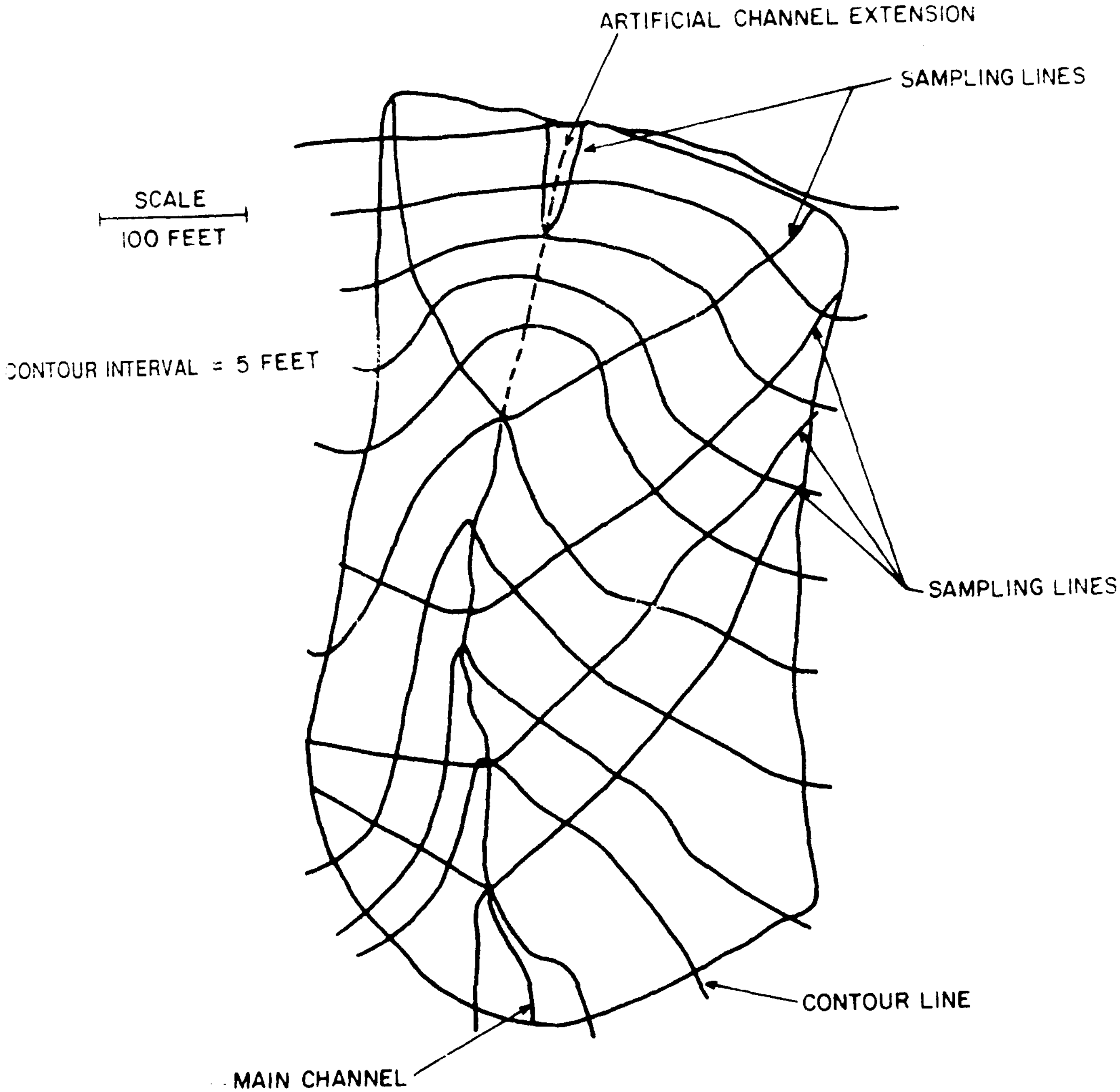


Figure 1. Example watershed for geometric data.

In small watersheds where swales provide channels for water flow, the a and b parameters can be estimated from the contributing side slope geometry. If the contributing side slopes (planes) have inclinations of 1/Z1 and 1/Z2, respectively, then the a1 coefficient becomes:

$$a1 = \left(\frac{2}{Z1 + Z2}\right)^{\frac{1}{2}} \left[(1 + Z1^{2})^{\frac{1}{2}} + (1 + Z2^{2})^{\frac{1}{2}}\right] \qquad \text{[Eq 3]}$$

where Z1 = the horizontal distance needed to move 1 foot vertically on contributing slope 1

Z2 = the value for contributing slope 2.

For swale or triangular channel flow, the value of b1 is always 0.5. The parameters a2 and b2 are found in a similar fashion where

$$a2 = [2\ (Z1 + Z2)]^{\frac{1}{2}} \qquad \text{[Eq 4]}$$

and b2 is always 0.5 for a swale or triangular channel.

Similar relationships for other channel shapes can be developed from geometric properties. For many channels, the b coefficients range between 0.4 and 0.6. Wide channels, such as big rivers or wide arroyos, often have b values of less than 0.3.

Example 2: Determining a and b parameters for a swale channel cross section.

Using the values from Example 1,

Slope 1 = 0.090	Z1 = 1/slope 1 = 11.1
Slope 2 = 0.119	Z2 = 1/slope 2 = 8.4

$$a1 = \left[\frac{2}{11.1 + 8.4}\right]^{\frac{1}{2}} \left(\left[1 + (11.1^{2})\right]^{\frac{1}{2}} + \left[1 + (8.4^{2})\right]^{\frac{1}{2}}\right)$$

$$= (0.32)\ (19.60) = 6.27$$

$$b1 = 0.5$$

$$a2 = (2\ [11.1 + 8.4])^{\frac{1}{2}} = 6.24$$

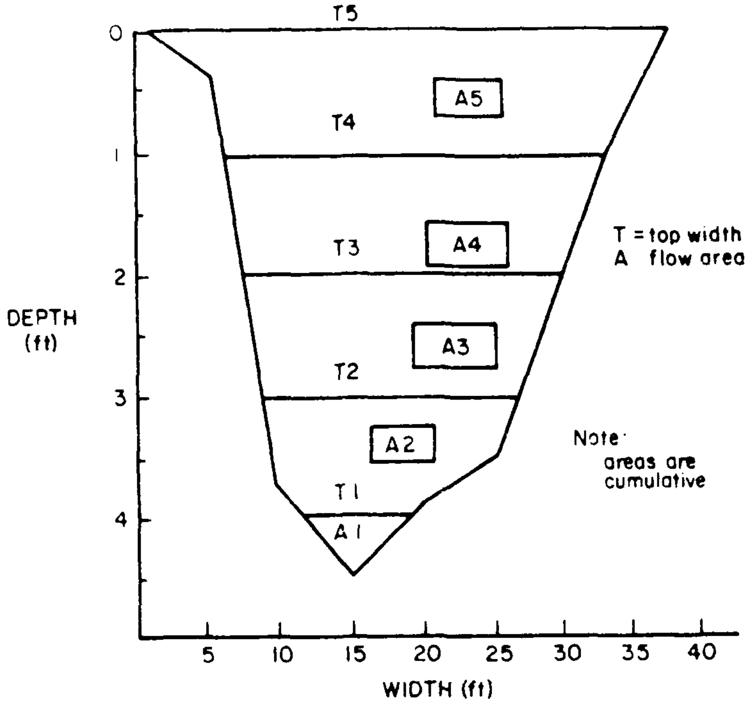
$$b2 = 0.5$$

Example 3: Determining a and b parameters if the channel cross section is not a swale.

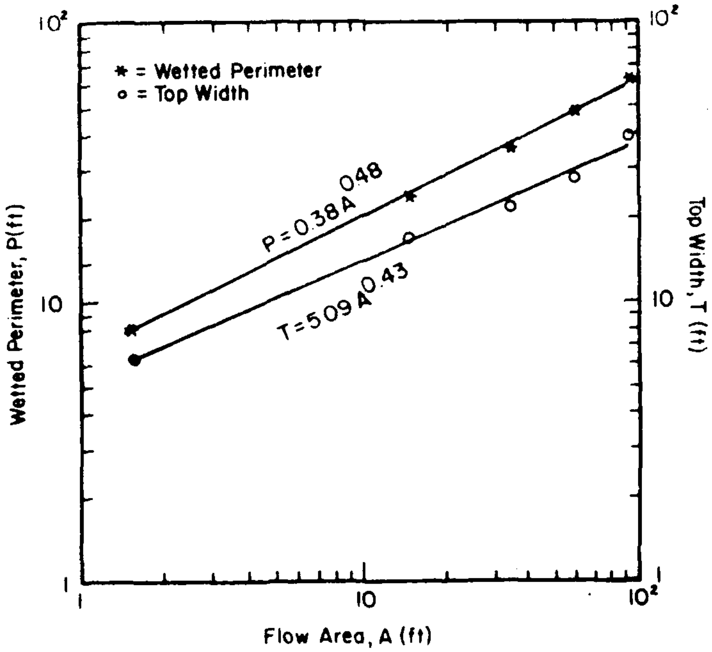
Figure 2a shows an actual channel cross section subdivided by depth zones. The flow area and wetted perimeter for the channel in Figure 2a are listed in Table 2.

Figure 2b shows the best-fit lines for the cross-sectional properties. The parameters are:

a1 = 6.38	b1 = 0.49
a2 = 5.09	b2 = 0.43



(a)



(b)

Figure 2. Cross-sectional properties of a channel site at Pinyon Canyon, Colorado.

Table 2

Channel Data for Figure 2a

Depth (ft)	Wetted Perimeter (ft)	Top Width (ft)	Flow Area (sq ft)
0.05	8.05	6.18	1.56
1.5	23.68	16.95	14.46
2.5	35.14	22.13	34.22
3.5	46.57	27.87	59.18
4.5	62.15	39.17	91.30

Note that the best-fit lines in Figure 2b are based on log-log data transformations. When measurements of channel cross sections are not available, it is recommended that the parameters be estimated from the contributing side slopes as presented in Example 2. This estimation procedure may create errors in the model computations if the channels are wide or extremely steep and narrow.

Soil Characteristics

There are two general types of information related to soils: hydrologic/infiltration properties and erosion/sediment characteristics. Field studies and soil samples are the best way to determine the necessary information. However, extensive data collected during the past several years can be used to estimate much of this information. Table 3 shows the soil parameters.

The user needs to obtain the soil classification textures for soils within the watershed. This data is used often when determining values for input parameters.

Infiltration Properties

Certain hydrologic properties of the soil must be obtained to properly model the infiltration process using the Green-Ampt model. As a minimum, soil textural classifications are required. Parameters in the infiltration model include: the hydraulic conductivity in the wetted zone (Kw), the porosity (n), the final (Sw) and initial (Si) soil saturation (ratio of volume of water in a sample to volume of void space), and the average capillary suction head (Yc).

For simplicity, use the fixed values n = 0.5 and Sw = 1.0. Better estimates of n can be made, but the improvement in model accuracy is not usually marked.

Table 3

Soil Parameters

ARMSED Variable	MSED Submodel	Description
WETK (in./hr)	1,3	Hydraulic conductivity, Kw
SAVE or SUC (in.)	1,3	Capillary suction, Yc
POROS	1,3	Soil porosity, n
SW	1	Final soil saturation, Sw
SI	1	Initial soil saturation, Si

Si can be roughly estimated from antecedent rainfall conditions, temperature data, and a knowledge of the soil. Because the Si value is used for calibration in conjunction with the Yc value, only an intuitive realistic initial estimate of Si is needed. Such estimates or ranges of values can be made from field capacity and wilting point values. For wet conditions, Si is 0.8 and greater; for very dry conditions, Si is about 0.15; and for average conditions, Si is about 0.5.

The following relationship can be used to find Si if water content data are available. The gravimetric water content relationship is defined as:

$$(S)(e) = (w)(G) \qquad \text{[Eq 5]}$$

where S = saturation
e = n/(1-n)
w = gravimetric water content
G = the specific gravity of the soil particles (G = 2.65 is suggested)

Kw and Yc are the remaining infiltration parameters to be determined. The Green-Ampt infiltration model can be rewritten as:

$$f = Kw \frac{(F + Hc)}{F} \qquad \text{[Eq 6]}$$

where f = infiltration rate
Kw = hydraulic conductivity in the wetted zone
F = infiltrated volume (an equivalent depth)
Hc = a grouping of soil parameters, [(Sw-Si)n(Yc)].

Kw represents the infiltration rate when the soil nears saturation. Model calibration experience has shown that Kw is a more important parameter than Yc. Therefore, the other parameters that constitute Hc can be estimated, if needed. Methods for determining Kw and Yc are described in the next two sections.

Infiltration Parameters From Field Data

Except for soils that have been analyzed, field data for values of Kw and Yc are not available. In general, soils are anisotropic (exhibit different properties along different axes of measurement) and heterogeneous in their physical properties of conductivity, porosity, and capillary pressures, which may vary by significant amounts over very short distances. Therefore, a mathematical analysis based on data from only one or two extensively studied samples may not be meaningful. Accurate watershed simulation requires calibration of the parameters to compensate for neglected processes and inadequacies in theory. The parameters of the infiltration model, particularly Kw, require such calibration; therefore, good initial estimates of Kw and Yc are needed. Recommended methods for conducting field infiltration tests using rainfall simulation experiments are presented in the Appendix.

Example 4: Determining infiltration parameters from rainfall simulation experiments using the standard approach (see Figures 3 and 4).

If rainfall simulator data are available, the following standard approach can be used to obtain estimates of Kw and Yc.

1. Plot the infiltration rate and infiltrated volume as a function of time. The infiltration rate is the measured rainfall rate minus the measured runoff rate (inch per hour). Figure 3 shows an example of plotted infiltrometer data from Pinyon Canyon (Fort Carson training area), Colorado.

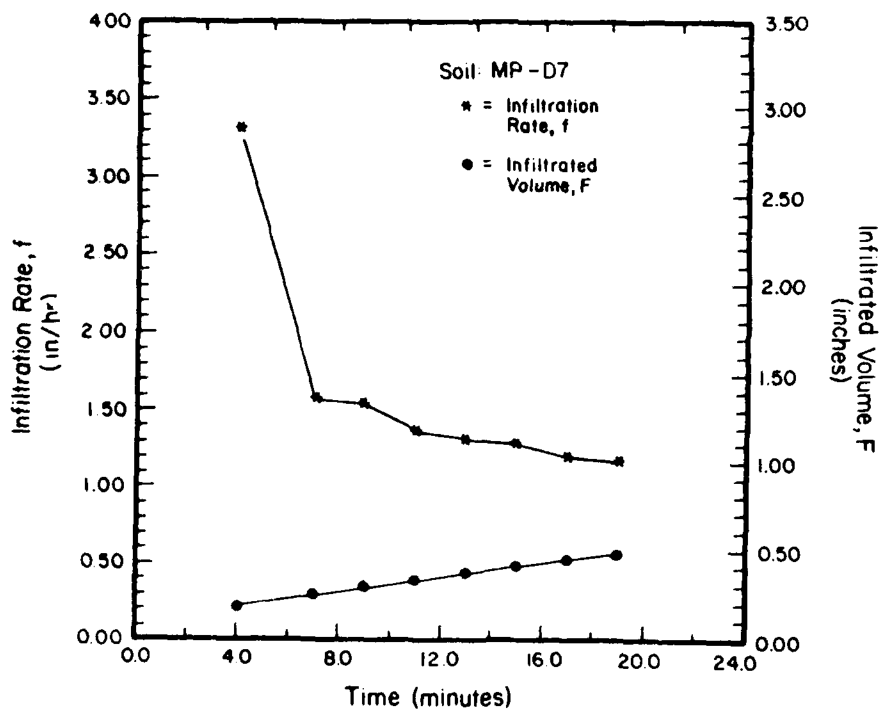


Figure 3. Infiltration rates and volumes for soil MP-D7.

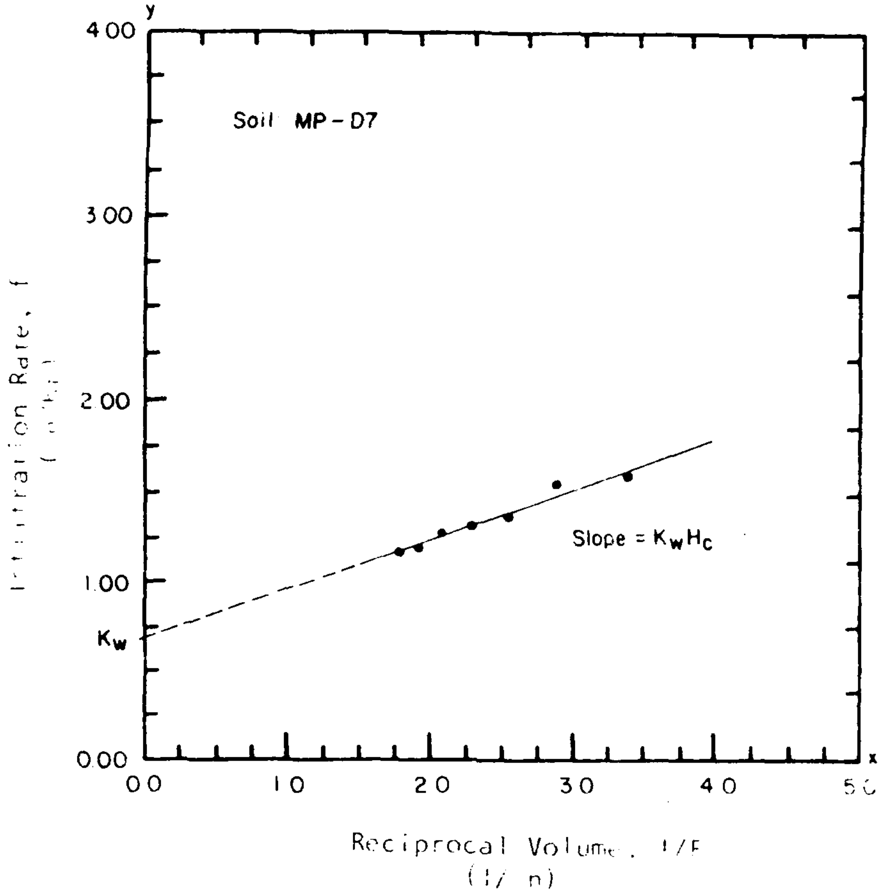


Figure 4. Plot for determining Kw and Hc for soil MP-D7.

2. Plot the infiltration rate versus the reciprocal of the infiltrated volume using the curves plotted in Step 1. Figure 4 shows the result of plotting this type of curve from the data given in Figure 3.

3. The curve of infiltration rate as a function of the reciprocal of infiltrated volume is nearly a straight line, at least to the extent that the Green-Ampt equation represents the actual soil process. If a straight line is fitted to this data (excluding the first point and the last point as they include errors related to rainfall simulator operation and the noninfiltration effects), the y-intercept is Kw and the slope is (Kw)(Hc). Thus estimates of Kw and Yc can be obtained by measuring the slope and intercept of the line fit to the data.

For this soil, w = 0.241 and n = 0.617. Using Equation 5, Si can be determined as 0.396. Kw is determined (as 0.663 in./hr) from the y-intercept in Figure 4. Hc (0.962) is determined using the slope. Then, using the relationship Hc = (Sw - Si)n(Yc), where Sw = 1.0, Yc is determined to be 2.58 in.

Sometimes the best-fit line has a negative intercept which does not have a physical interpretation. Therefore, the steady rate approach is suggested as:

1. Plot and examine the data using the standard approach described above and shown in Figure 5.

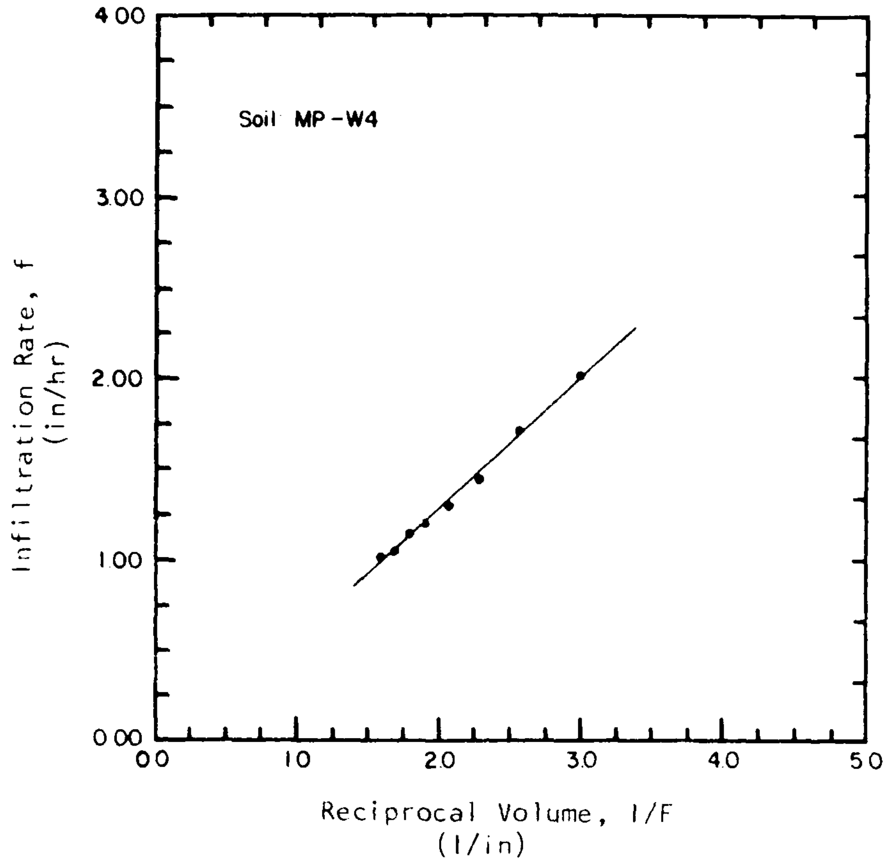


Figure 5. Infiltration rates and volumes for soil MP-D7.

2. Use an average infiltration rate calculated from the last three steady rate values. This average value is assumed to be Kw.

3. Calculate a revised set of data pairs as y = (f - Kw)/Kw and x = 1/F. Note that the first data point is not used since it represents an amount of water that has been infiltrated and intercepted. The last data point has also been excluded from the figures and the analysis because it represents water that was on the soil surface and ran off after the rainfall stopped.

4. Fit a no-intercept straight line to the revised data [a no-intercept line passes through the data point (0,0)]. The slope of this line is (Kw)(Hc) as shown in Figure 6.

Both approaches are suggested as methods of obtaining the necessary soil hydrologic characteristics. It is obvious that the data plotted in Figure 6, although better described by the standard approach, produces more physically realistic values when the steady rate approach is used. The standard approach should be used first, then if the intercept Kw is negative, the steady rate approach should be used.

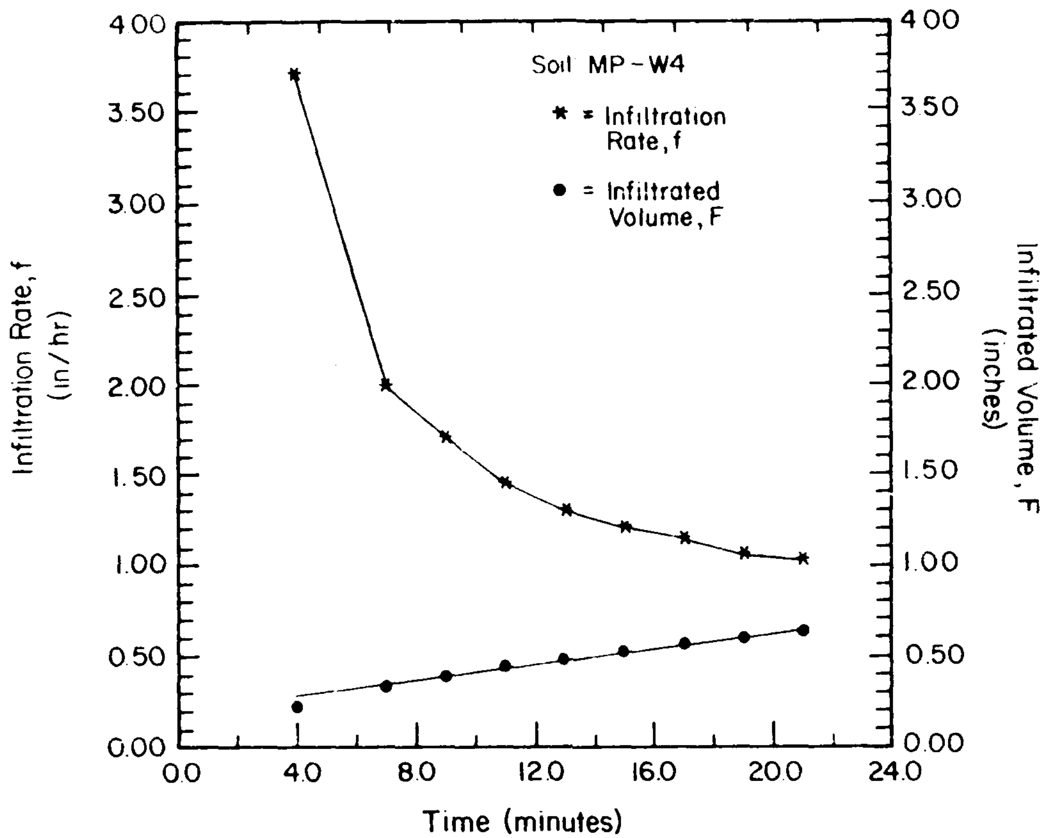


Figure 6. Plot for determining Kw and Hc for soil MP-W4.

Infiltration Property Estimates from Soil Texture

If field data are not available, reasonable first estimates can be taken from Table 4. This table requires that the user has an estimate of soil type (i.e., texture). Soil type information could be obtained from the U.S. Department of Agriculture (USDA) Soil Conservation Service, the Soils Information Retrieval System (SIRS)[2] or soil classifications based on field samples and laboratory analysis.

Surface conditions can change infiltration rates. There is a general tendency of increased infiltration rate with increased vegetative cover. This effect is probably a result of the vegetation creating longer flow detention and, hence, longer infiltration opportunity times. There is no equation available to include surface effects on infiltration.

[2]Pamela J. Thompson, et al., *An Interactive Soils Information System User's Manual*, Technical Report N-87/18/ADA185153 USACERL, July 1987).

Table 4

Hydrologic Soil Characteristics Related to Soil Type*

Soil Type	Porosity (Fraction)	Hydraulic Conductivity Kw (in./hr)	Capillary Soil Suction, Yc, (in.)
Sand	0.44	6.61	1.9
Loamy Sand	0.44	2.00	2.4
Sandy Loam	0.45	0.74	4.3
Loam	0.46	0.48	3.5
Silty Loam	0.50	0.40	6.6
Sandy Clay Loam	0.40	0.63	8.6
Clay Loam	0.46	0.35	8.2
Silty Clay Loam	0.47	0.29	10.7
Sandy Clay	0.43	1.02	9.4
Silty Clay	0.48	0.19	11.5
Clay	0.48	0.14	12.4

*Derived from W. J. Rawls, D. L. Brakensiek, and N. Miller, "Green-Ampt Infiltration Parameters From Soils Data," *Journal of Hydraulic Engineering*, Vol 109, No. 1 (ASCE, January 1983), pp 62-70; and B. J. Cosby, et al., "A Statistical Exploration of the Relationships of Soil Moisture Characteristics to the Physical Properties of Soils," *Water Resources Research*, Vol 20, No. 3 (June 1984), pp 682-690.

Erosion/Sediment Parameters

If sediment yield and sediment routing are to be modeled, soil data that describe the properties of the sediment are required. These properties are described using (1) sediment size analysis, (2) sediment detachment coefficients, (3) plasticity index, and (4) erosion rate constant for cohesive soils. Sediment transport parameters are fixed as constants in the ARMSED program. As a minimum, soil textural classifications are needed to estimate the parameters for the model. Table 5 shows the erosion/sediment parameters.

Table 5

Input Data for Erosion/Sediment Parameters

ARMSED Variable	Unit	MSED Submodel	Description
D	mm	1,3	Sediment size
P or PF	decimal fraction	1,3	Fraction of sediment finer than or equal to size D
DCOEFF	-	1	Rainfall splash detachment coefficient
DOF	--	1	Overland flow detachment coefficient
CHDOF or ADF	--	1,3	Channel flow detachment coefficient
COHM	lb/sq ft/sec	1,3	Erosion rate constant (use 0.00012)
PLASI	--	1	Soil plasticity index

Sediment Size Data

Sediment size input data consists of sediment size, D (in millimeters), and the decimal fraction, P, of the sediment that is finer than or equal to size D. Sediment size data should include onsite size distributions and transported material distributions. Stock ponds or other locations where sediments have been deposited are good locations from which to obtain transported material samples. Use of both distributions helps during model calibration to confirm that the model is transporting the correct size fractions from the correct sediment supply. Size distributions are obtained from sieve analyses of duplicate samples. Soil descriptions for common size distributions are given in Table 6. A particle size distribution for the in situ soil is needed to determine the resultant sediment transport.

If field samples cannot be obtained, an estimate of the D50 (grain size at which 50 percent of the material is finer by weight) sediment size (median grain size) can be used. Some information may be available from USDA Soil Conservation Service Reports, SIRS, or State soil surveys. Textural classification is one method to estimate a D50

Table 6

Soil Descriptions For Common Sediment Size Breakdowns

Class	Size (mm)	
Very coarse sand	2-1*	2-1**
Coarse Sand	1-.5	1-.5
Medium Sand	.5-.25	.5-.25
Fine sand	.25-.125	.25-.10
Very fine sand	.125-.062	.10-.05
Coarse silt	.062-.031	.05
Medium silt	.031-.016	--
Fine silt	.016-.008	to
Very fine silt	.008-.004	.002
Coarse clay	.004-.002	less than
Medium clay	.002-.001	.002
Fine clay	.001-.0005	--
Very fine clay	.0005-.00024	--

***Engineering Hydraulics*, H. Rouse Ed. (Wiley and Sons, 1951).
**Typical SCS sediment sizes.

sediment size or size distribution. This requires use of a clay-silt-sand chart (Figure 7). After starting with a textural class name, a point is selected in a central part of the class name polygon. Corresponding percent sand, percent silt, and percent clay values are used to plot a gradation curve. The percents are plotted as 100 percent finer than 2 mm (coarse sand), silt percent plus clay percent finer than 0.05 mm (silt), and clay percent finer than 0.002 mm (clay). The gradation curve consists of three points (sand, silt, and clay) and can be described for mathematical purposes by D50 or, preferably, by the individual size fractions. If a soil is classified as a clay loam, it may be (from Figure 7 or Table 7), 32 percent sand and 34 percent clay which indicates 34 percent silt. A reasonable lower size limit is 0.00024 mm.

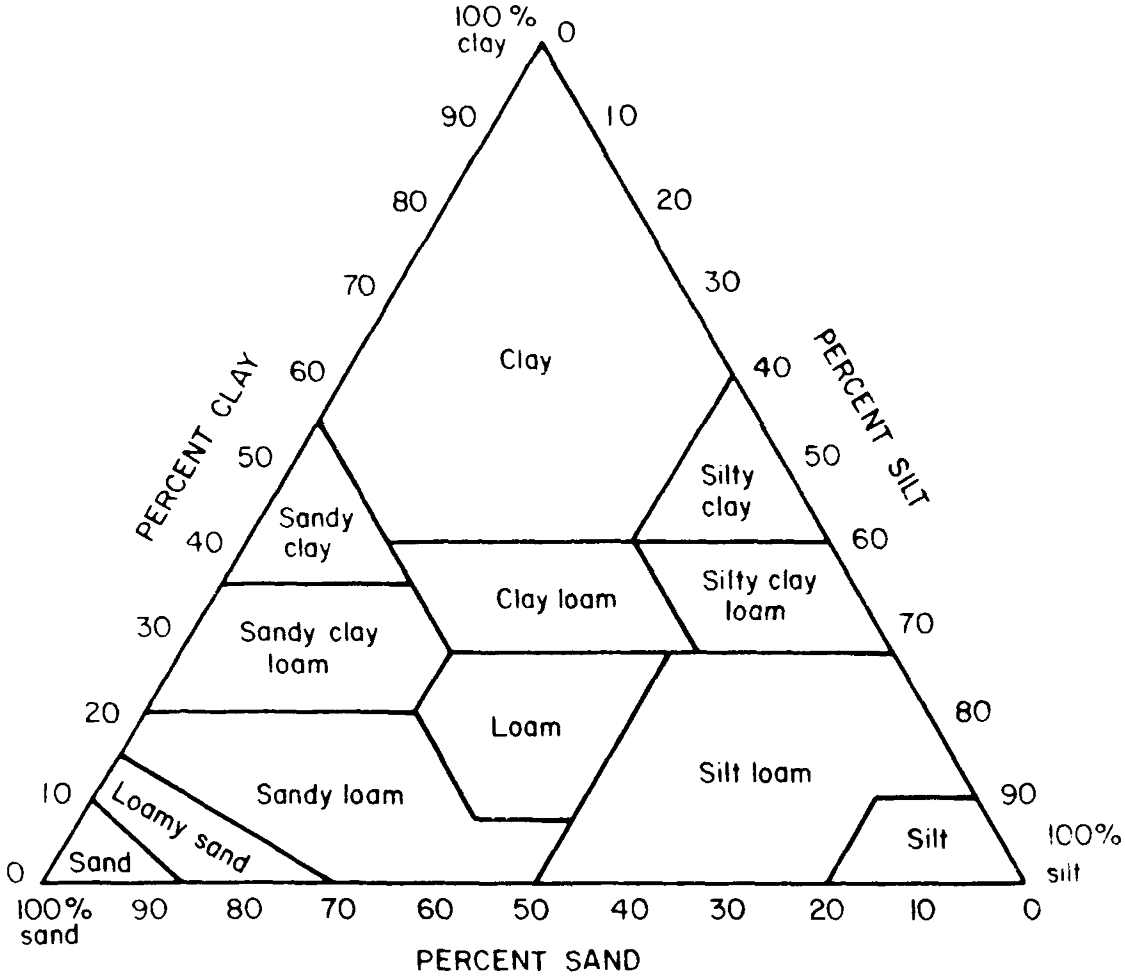


Figure 7. Soil textural classification graph for estimating size fractions.

Once a size distribution has been chosen, the distribution is subdivided into representative size fractions, if desired. The procedure for doing this is described in Chapter 3. Sand-silt-clay percentages from Table 7 are weighted then plotted on logarithmic grain size-arithmetic probability paper. A rough estimate of transport using the D50 size is possible, but because the models are formulated for different size fractions, more information is gained if several size fractions are used. A maximum of 10 sizes is allowed in ARMSED.

Although this is a rather crude approach, it does allow you to develop useful model inputs from sparse data. Actual sieve samples of the transported materials would provide a check of the model and the assumed input distribution by determining if the transported material is equal to or finer than the onsite material.

Table 7

Midpoint Percentages for Soil Types*

Soil Type	Percent of Sand	Percent of Silt	Percent of Clay
Sand	91	5	4
Loamy Sand	81	13	6
Sandy Loam	66	25	9
Loam	56	34	10
Silty Loam	10	81	9
Sandy Clay Loam	65	12	23
Clay Loam	36	38	26
Silty Clay Loam	10	64	26
Sandy Clay	54	8	38
Silty Clay	7	52	41
Clay	21	20	59

*Modified from B. J. Cosby, et al., "A Statistical Exploration of the Relationships of Soil Moisture Characteristics to the Physical Properties of Soils," *Water Resources Research*, Vol 20, No. 3 (June 1984), pp 682-690.

Sediment Detachment Coefficients

Sediment is detached by raindrop impact and the energy of flowing water. Soil detachment coefficients for raindrop splash (DCOEFF), overland flow (DOF) and channel flow (CHDOF) runoff are used to determine sediment supply. A raindrop splash exponent is also needed. These coefficients are initially estimated but are often subsequently calibrated. The rainfall splash detachment coefficient is a function of soil type, soil structure, moisture conditions, and cohesion. There is not enough information to determine the relationship between the splash coefficient and other soil characteristics, therefore, use a fixed value of 0.001. Use a fixed value of 2.0 for the raindrop splash exponent.

The overland flow detachment coefficient can be estimated from the equation:

$$DOF = 10^{(0.2264-0.0533\ Pc)} \qquad \text{[Eq 7]}$$

where: DOF = the overland flow detachment coefficient
Pc = clay percentage.[3]

If Pc is less than 5 percent, then DOF equals 1.0; if Pc is greater than 60 percent, DOF equals 0.001. The channel flow detachment coefficient can be fixed to the same value as the overland flow detachment coefficient unless otherwise determined by measured or calibrated data.

Plasticity Index

The plasticity index is the difference between the liquid limit and the plastic limit of a soil.

$$PI = LL - PL \qquad \text{[Eq 8]}$$

where PI = the plasticity index
LL = the liquid limit
PL = the plastic limit.

The liquid limit and plastic limits are defined as the water content at which the soil behaves differently as determined by Atterberg limit tests. For example, montmorillonite clays may have plastic indices of 100 to 600 percent while kaolinite clay may have indices of only 10 to 25 percent. Obviously, the plasticity index is a function of the clay mineralogy.

Equation 8 is valid for plasticity indices less than about 50 percent. It is an approximation derived from empirical studies and may need to be adjusted according to field data.

Smerdon and Beasley[4] also related PI to Pc. An approximate estimate of PI can be found from:

$$\log(PI) = 0.5729 + 0.0218\ Pc \qquad \text{[Eq 9]}$$

Erosion Rate Constant for Cohesive Soils

A final erosion parameter is the *erosion rate constant for cohesive soils* (COHM). This parameter is also difficult to estimate and a value of 0.00012 is recommended.

---

[3]G. K. Cotton and R. M. Li, "Simplified Sediment Yield Model for Small Area Disturbances on Surface-mined Lands," *Proceedings of the International Conference on Soil Erosion and Conservation* (January 16-22, 1983).
[4]E. T. Smerdon and R. P. Beasley, "Critical Tractive Forces in Cohesive Soils," *Agricultural Engineering* (January 1961), pp 26-29.

Erosion Parameter Estimates from Soil Towers

If no better data are available, use Table 8 to determine erosion parameters. The values in the table were computed following the procedures described above. The Universal Soil Loss Equation (USLE) K Factor is used later to determine the flow resistance.

Surface Characteristics

Surface conditions determine how the water runs off the land. Bare, smooth surfaces let water run off faster, which increases erosion. Conversely, rough, rocky and/or vegetated surfaces retard water flow and help prevent erosion. Surface conditions affect both overland flow and channel flow. Ground and canopy cover density determine rainfall interception volumes. Ground cover density is also used to compute overland flow resistance. Table 9 shows parameters for surface characteristics.

Cover Density

Cover density (CANCOV and GRNCOV) data can be acquired by onsite inspection or by use of aerial photography. Figure 8 can help in the determination. If aerial photography is used, some onsite inspection is also needed for ground truth. Canopy cover interception storage (VC) and ground cover interception storage (VG) values are more difficult to determine. It is necessary to specify vegetation types and distribution by use of a vegetation map so that realistic interception volumes can be computed. The tremendous range in the reported values makes it difficult to select an appropriate number. Typical values for conifers average 0.1 in. and ground cover interception is estimated at approximately 0.05 to 0.1 in. Use values of 0.1 in. if no better estimates are available.

Estimates of impervious area (PIMP) and area in depression storage (DPRES) are also required. These can be estimated by using Figure 8. Use zero for both values if no other information is available.

Table 8

Parameter Estimates Based on Soil Type

Texture	K	PI	DOF
Sand	0.13	4	1.00
Loamy Sand	0.15	5	0.84
Sandy Loam	0.24	6	0.60
Loam	0.44	6	0.58
Silty Loam	0.59	6	0.58
Sandy Clay Loam	0.13	12	0.10
Clay Loam	0.17	14	0.023
Silty Clay Loam	0.38	14	0.080
Sandy Clay	0.10	25	0.017
Silty Clay	0.27	30	0.012
Clay	0.15	72	0.001

Table 9

Parameters for Surface Characteristics

ARMSED Variable	Unit	MSED Submodel	Description
CANCOV	percent	1	Percent of area covered by vegetative or other canopy
GRNCOV	percent	1	Percent of area covered by vegetative or other ground cover
VC	in.	1	Potential depth of rainfall storage on the canopy cover
VG	in.	1	Potential depth of rainfall storage on the ground cover
PIMP	percent	1	Percent of area with impervious cover
DPRES	decimal fraction	1	Fraction of plane that does not contribute to flow
XN	--	1,3	Manning's roughness coefficient for channels
ADW	--	1	Maximum roughness coefficient for overland flow

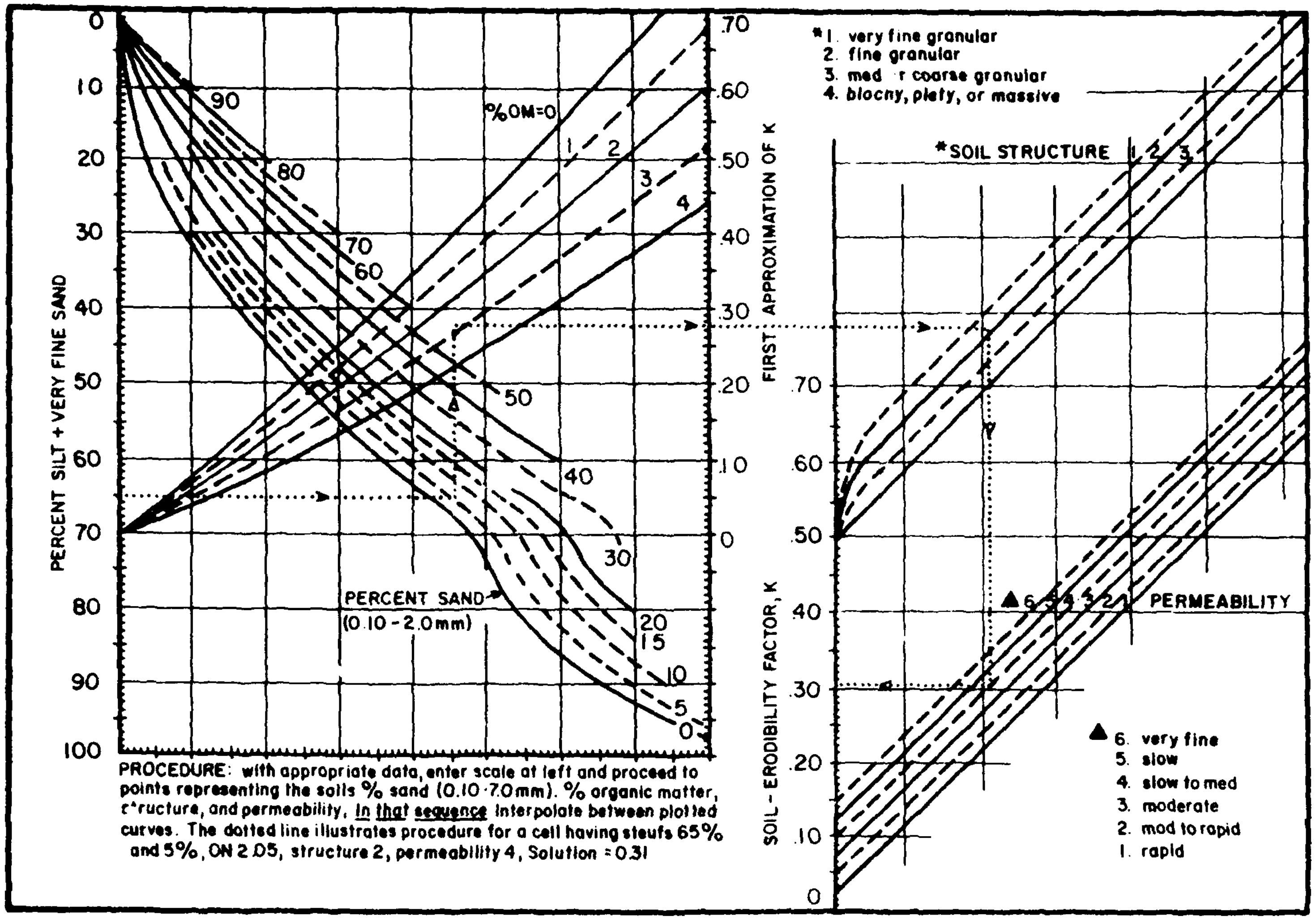


Figure 8. Nomograph for determining the USLE K-factor.

Flow Resistance

Two types of flow resistance are used in ARMSED; overland and channel. Overland flow resistance is considered in ARMSED through use of a lower and an upper value. The lower value is fixed in the model at 100. Suggested values for the upper overall resistance factor (ADW) are given in Table 10.

ADW can be estimated using the K factor from the USLE.

$$ADW = 4220K^{-0.75} \qquad \text{[Eq 10]}$$

If K is greater than 0.6, use K = 0.6; if K is less than 0.07, use K = 0.07. The K factor can be estimated from the nomograph in Figure 9. The permeability classes for this nomograph are defined in Table 11.

Channel surfaces also offer resistance to water flow. Resistance to channel flow as indicated by Manning's roughness coefficient (n) can vary from about 0.02 for smooth channels, such as flat-bedded arroyos, up to 0.10 for very weedy, brushy channels. If the channel contains short grass or rocks, a value of 0.035 is suggested. The higher the value of n, the slower the water flows and the less erosion occurs. Typical values for n are given in Table 12.

Table 10

Overall Resistance Parameters for Overland Flow*

Surface	Range of Parameter
Concrete or Asphalt	24 - 108
Bare Sand	30 - 120
Graveled Surface	90 - 400
Bare Clay - Loam Soil (eroded)	100 - 500
Sparse Vegetation	1000 - 4000
Short Grass Prairie	3000 - 10000
Bluegrass Sod	7000 - 40000

*Source: D. A. Woolhiser, "Simulation of Unsteady Overland Flow," *Unsteady Flow in Open Channels*, Eds. K. Mahmood and V. Yevjevich (Water Resources Publications, 1975).

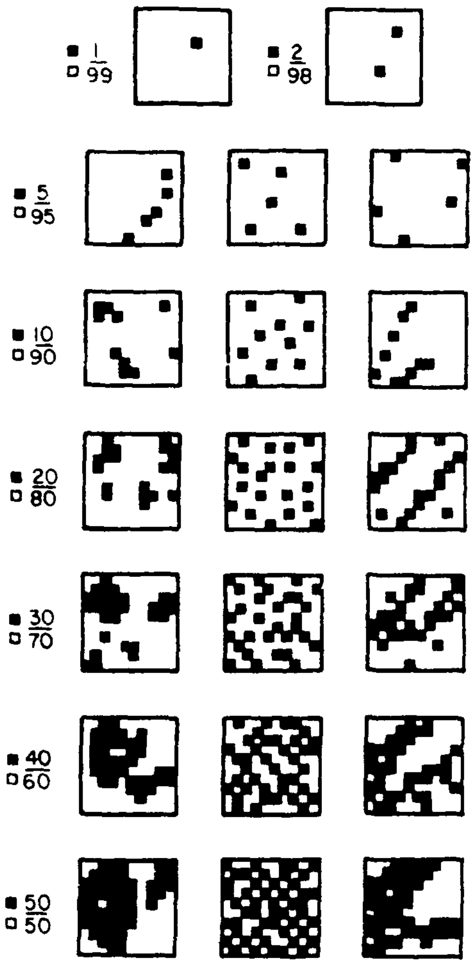


Figure 9. Guide for estimating bare soil, canopy, or other surface cover.

Table 11

Representative Soil Types and Hydraulic Conductivities

Representative Soil Type	Permeability
Sandy Clay	Very Slow
Silty Clay	Very Slow
Clay	Very Slow
Sandy Clay Loam	Slow
Silty Clay Loam	Slow
Clay Loam	Slow
Loam, Silty Loam	Slow to moderate
Loamy Sand	Moderate to rapid
Sand	Rapid

Table 12

Values of the Roughness Coefficient, n

Channel Type and Description	Minimum n	Normal n	Maximum n
NATURAL STREAMS			
1. Minor streams (top width at flood stage < 100 ft)			
a. Stream on plain			
(1) Clean, straight, full stage, no rifs or deep pools	0.025	0.030	0.033
(2) Same as above, but more stones and weeds	0.030	0.035	0.040
(3) Clean, winding, some pools and shoals	0.033	0.040	0.045
(4) Same as above, but some weeds and shoals	0.035	0.045	0.050
(5) Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
(6) Same as 4, but more stones	0.045	0.050	0.060
(7) Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
(8) Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
(1) Bottom: gravels, cobbles and a few boulders	0.030	0.040	0.050
(2) Bottom: cobbles with large boulders	0.040	0.050	0.070
2. Major streams (top width at flood stage > 100 ft) The n value is less than that for minor streams of similar description because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	-----	0.060
b. Irregular and rough section	0.035	-----	0.100

Rainfall Characteristics

The rainfall parameters are shown in Table 13. The NRAIN value must be equal to or greater than one. A minimum value of four is suggested even for constant intensity to avoid computational problems in the infiltration routine. Storms with variable intensities will require more increments. The ending times are fixed by the data set or the way the rainfall record is developed.

There are two approaches to developing intensity data; use measured events or generate a design storm. Measured events are helpful in calibrating the model if runoff data are also available. Unfortunately, measured rainfall and runoff data are not always available.

Design storms, on the other hand, are more useful in planning because they represent extreme conditions with which different land management practices can be compared. The frequency of occurrence, duration of the storm, and storm depth depend on the climatic and physiographic setting of the watershed. Frequency-duration-depth information has been analyzed by the National Weather Service (NWS) and presented as maps and equations for the United States.[5] The frequency of rainfall is an estimate of how often, on average, a particular intensity would occur. Therefore a 100-year storm occurs, on average, every 100 years; it has a 1 percent chance of occurring in any one year. The storm duration is usually selected as 30, 60, 120, 240, etc., minutes. As discussed earlier, rainfall duration, like runoff duration, should exceed the time it takes water to travel from the most remote point on a watershed to the outlet. If frequency and duration are selected, a given depth is unique to that combination because of a deterministic relationship between the three quantities.

Table 13

Input Data for Rainfall Characteristics

ARMSED Variable	Unit	MSED Submodel	Description
NRAIN	--	1	Number of rainfall increments.
RAINOLD	in./hr	1	Rainfall intensity or rate during an increment.
RAINT	min	1	Ending time of an increment.

[5]D. M. Hershfield, *Rainfall Frequency Atlas of the United States for Duration From 30 Minutes to 24 Hours and Return Periods From 1 to 100 Years*, Technical Report No. 40 (U.S. Weather Bureau, 1961); *Precipitation-Frequency Atlas of the Western United States: Volume IV-New Mexico* (National Oceanic and Atmospheric Administration [NOAA], 1973).

The work by Wenzel and Melching[5] with ARMSED and design rainfall indicated that management decisions would be the same if a constant rate rainfall were used instead of a more realistic temporal distribution. They caution, however, that an event that is distributed in time in a more realistic manner can provide better estimates of the water and sediment yields. Their study also indicated for the two watersheds that they studied, a storm of 30 minutes duration provided a good balance between the effects of a too short storm and a too long storm. This may not be the case for all watersheds, but it can provide a starting point from which to consider a variety of rainfall durations.

If the user wants to subdivide a storm of a selected duration and depth into increments, the following approaches are suggested.

1. Use a constant rainfall rate as

$$I = V/T \qquad \text{[Eq 11]}$$

where I = rainfall intensity (in./hr)
V = total rainfall depth (in.)
T = rainfall duration (hours).

A minimum of four increments is suggested.

2. Use a variable rainfall rate as

$$Ii = (V/T)\,(T^*i^{0.56} - T^*i\text{-}1^{0.56})/(T^*i - T^*i\text{-}1) \qquad \text{[Eq 12]}$$

where Ii = intensity in increment period i (in./hr)
T*i = Ti/T, a dimensionless ending time [Ti is the actual ending time of the increment (in hours)].

The second approach is based on an analysis of measured data.

Example 5: Design storm temporal resolution.

Rainfall depth = 2 in.

Rainfall duration = 1 hour

Rainfall frequency = 100 years

Approach 1:

I = 2/1 = 2 in./hr constant rate

Use four 15-minute increments as suggested with ending times of 15, 30, 45, and 60 minutes

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[5] Wenzel, H. G., Jr. and C. S. Melching, *An Evaluation of the MULTSED Simulation Model to Predict Sediment Yield*, Technical Report N-87/27/ADA185615 (USACERL, September 1987).

Approach 2:

Increment	Ending time (min)	T*	Ii (in./hr)
1	15	0.25	3.68
2	30	0.50	1.75
3	45	0.75	1.38
4	60	1.00	1.19

Two decimal places are sufficient to describe the rainfall intensity. Experience indicates that no single intensity should exceed about 10 in./hr. If any one does, it should be set to 10 in./hr and the others rescaled to yield a total rainfall as selected.

Miscellaneous Inputs

Miscellaneous inputs include geometry indices, reservoir characteristics, rainfall values, and sediment transport parameters as shown in Table 14.

IPLANE and ITYPE are identifiers that specify the type of unit or segment the program is processing. In MSED1, a value of IPLANE = 1 is a plane unit, whereas IPLANE = 2 is a subwatershed unit. In MSED3, ITYPE = 1 is for a channel segment and ITYPE = 2 is for a reservoir segment. TITLE is the identification of the simulation that will be printed on the output file.

DTIM and FTIM are the incremental and total simulation times, respectively, in minutes. DTIM is usually chosen to provide a fine enough resolution to note major changes in the hydrograph while avoiding excessive computation. For very small areas, up to 10 acres, a DTIM of 1 minute is appropriate. For larger areas, DTIM values of 5 to 10 minutes are reasonable. In any case DTIM should not exceed the time it would take water to move from the farthest point in an area to the outlet. The times suggested above should be within that limit in most cases.

FTIM, the total time of duration for the hydrograph, depends on the rainfall duration. Usually, 30 to 60 minutes beyond the rainfall duration will be sufficient. It should be noted that too much additional time will cause the program to stop when no more water is present. If the program does abnormally stop, FTIM should be reduced and the program rerun. In addition, DTIM should be an even fraction of FTIM and the values used in MSED1 should be the same as in MSED3.

The geometry inventory numbers of NPL, NWS, NCON, NRES, and NCH indicate how many planes, subwatersheds, connections to other basins, reservoirs, and channels, respectively, are to be processed. The NCON value is used to access water and sediment outflow files for channels that have previously been run through MSED3. The use of connections is not recommended unless specifically needed for extremely large watersheds.

The segment identifier, ISEG, is most useful in keeping track of the order of computational sequence. The ISEG number need not match the number of the plane or of the subwatershed, but the planes and subwatersheds should be computed in the order by which they contribute to the flow. Similarly, the channel segments should be identified by the order in which they logically occur.

Table 14

Miscellaneous Parameters

ARMSED Variable	Unit	MSED Submodel	Description
IPLANE ITYPE	--	1 3	Determines the type of unit being processed In MSED1, 1 = plane unit, 2 = subwatershed unit In MSED3, 1 = channel, 2 = reservoir
TITLE	--	1,3	Title of simulation
DTIM	min	1,3	Time increment of simulation. Must be the same in both MSED submodels
FTIM	min	1,3	Total duration of simulation
NPL	--	1,3	Number of plane units in the drainage basin Must be the same in both MSED submodels
NWS	_	1,3	Number of subwatersheds in the drainage basin Must be the same in both MSED submodels
ISEG	--	1,3	Segment (unit) number in sequential order 1, 2, 3 ...
IPRINT	--	1	1 = results printed -1 = results not printed
NRES	--	3	Number of small reservoirs (stock tanks) in the basin (seldom used)

Table 14 (Cont'd)

ARMSED Variable	Unit	MSED Submodel	Description
NCH	--	3	Number of channel units
IWS	--	3	Identification number of all subwatersheds flowing into a channel (3 maximum)
IPL	--	3	identification number of all planes flowing into a channel (2 maximum)
ICON	--	3	Identification number of the inflows from other basins
IUP	--	3	Identification number of upstream inflows to a channel - can be either reservoirs or other channels (3 maximum)
T	degrees Fahrenheit	1,3	Soil temperature
VCAP	acre-feet	3	Storage capacity of small reservoirs
VITL	acre-feet	3	Initial storage (if any) in small reservoir
SAREA	acres	3	Maximum surface area of small reservoir
POROS	decimal fraction	3	Porosity of sediment deposited in small reservoir (use 0.51)
QCON	cfs (cubic ft/sec	3	Discharge from connecting unit (seldom used)
GBOCON	cfs	3	Solid cfs from connecting unit (seldom used)

The MSED3 subprogram combines subwatershed and plane hydrographs to create channel hydrographs. The indexes of IWS, IPL, and IUP are used to identify which subwatersheds, planes, and upstream channels contribute to the channel segment being analyzed.

An important point to note is that MSED3 reads files that were created by MSED1 in the computational sequence specified by the user. The logic in MSED3 assumes that the first subwatershed is computed before the second subwatershed and the second before the third. Similarly, plane 1 should be computed before plane 2. The planes and subwatersheds can be intermingled, but each group should be in order. If a channel segment has upstream tributary channels, those channels must be computed before the channel in question. If not, the program cannot find a data set for the upstream flows.

Soil temperature, T, is used to adjust water viscosity for use in infiltration and sediment transport equations. Use monthly average air temperature for your area (degrees Fahrenheit) if no other value is known.

The reservoir characteristics of VCAP, VITL, SAREA, and POROS are used in the reservoir subroutine to move water and sediment through a small reservoir. The reservoir portion of MSED3 is simplistic but it is not well documented or tested with applications.

3 APPLICATION OF THE GUIDE

This section presents an application of the ARMSED model on a 40.5 acre rangeland watershed west of Albuquerque, New Mexico. This watershed has previously been modeled by Sabol and Ward.[7] It was chosen because of its small size and relatively good data base. The watershed will be analyzed using the techniques presented in this guide for both a design storm and a measured storm. The results are then compared with previous analyses using field data for the measured storm.

Design Storm Simulation Using Estimated Parameters

The watershed has been analyzed by Ward and Bolin.[8] In the first two applications, the data collected for that analysis is not used in order to demonstrate use of minimal information for estimating parameters for the model. Topographic and soils maps were used in data compilation (Figures 10 and 11).

Geometric Characteristics

The topographic map shows that the watershed has two tributaries to a third channel. The area draining to the longest tributary was made into a subwatershed and the other tributary was ignored because of its small contributing area. The watershed was subdivided into one subwatershed, two planes and one channel as shown by the schematic of Figure 12. Sample lines were drawn, areas measured, and slopes calculated for that configuration. The results of this analysis are presented in Table 15 for the different units in the watershed.

Five sampling lines were used to estimate overland flow slope. The a1 and a2 were calculated from side slope values as swale or v-shaped channels. Both b1 and b2 are equal to 0.5.

Soil Characteristics

The soils in the watershed were classified as sandy loam or clay loam. Suggested values from Tables 1, 4, and 6 were used to develop soil characteristics based on an area weighted average (i.e., how much of the unit was covered by a certain soil type). For example, WS1-L had 72.7 percent sandy loam with Kw = 0.74 and 27.3 percent clay loam with Kw = 0.35 by area. The area weighted average for hydraulic conductivity was calculated as

$$Kw = (0.727)\,0.74 + (0.273)\,0.35 = 0.63$$

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[7]G. V. Sabol and T. J. Ward, "Santa Barbara Hydrograph With Green-Ampt Infiltration," *Proceedings of the 1985 ASCE Watershed Management Symposium - Watershed Management in the Eighties*, Denver, CO (American Society of Civil Engineers [ASCE], 1985).

[8]T. J. Ward and S. B. Bolin, *A Study of Rainfall Simulators, Runoff and Erosion Processes, and Nutrient Yields on Selected Sites in Arizona and New Mexico*, Technical Completion Report, Project No. 1423672 (New Mexico Water Resources Research Institute, April 1988).

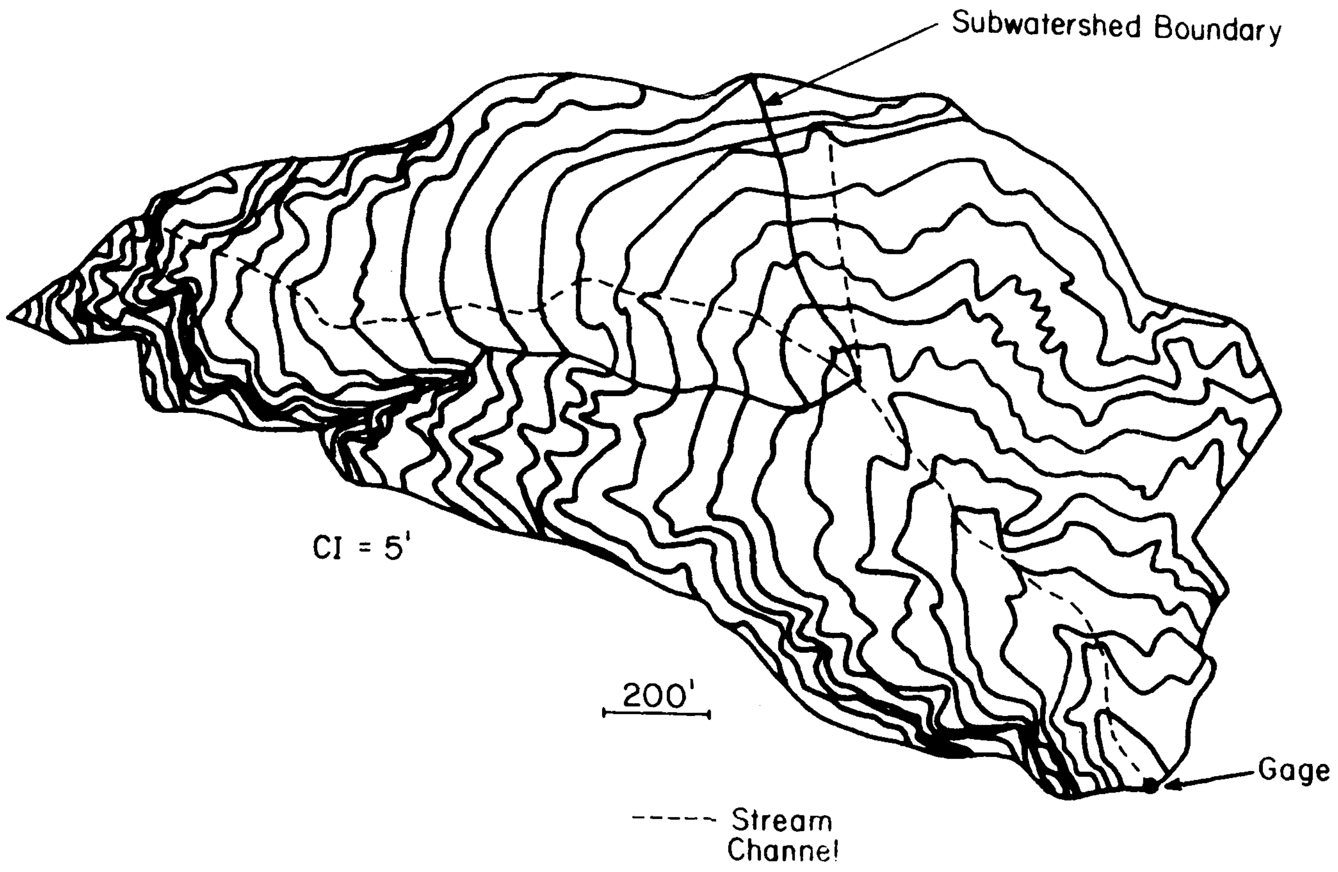

Figure 10. Topographic map of Albuquerque ARS Watershed II.

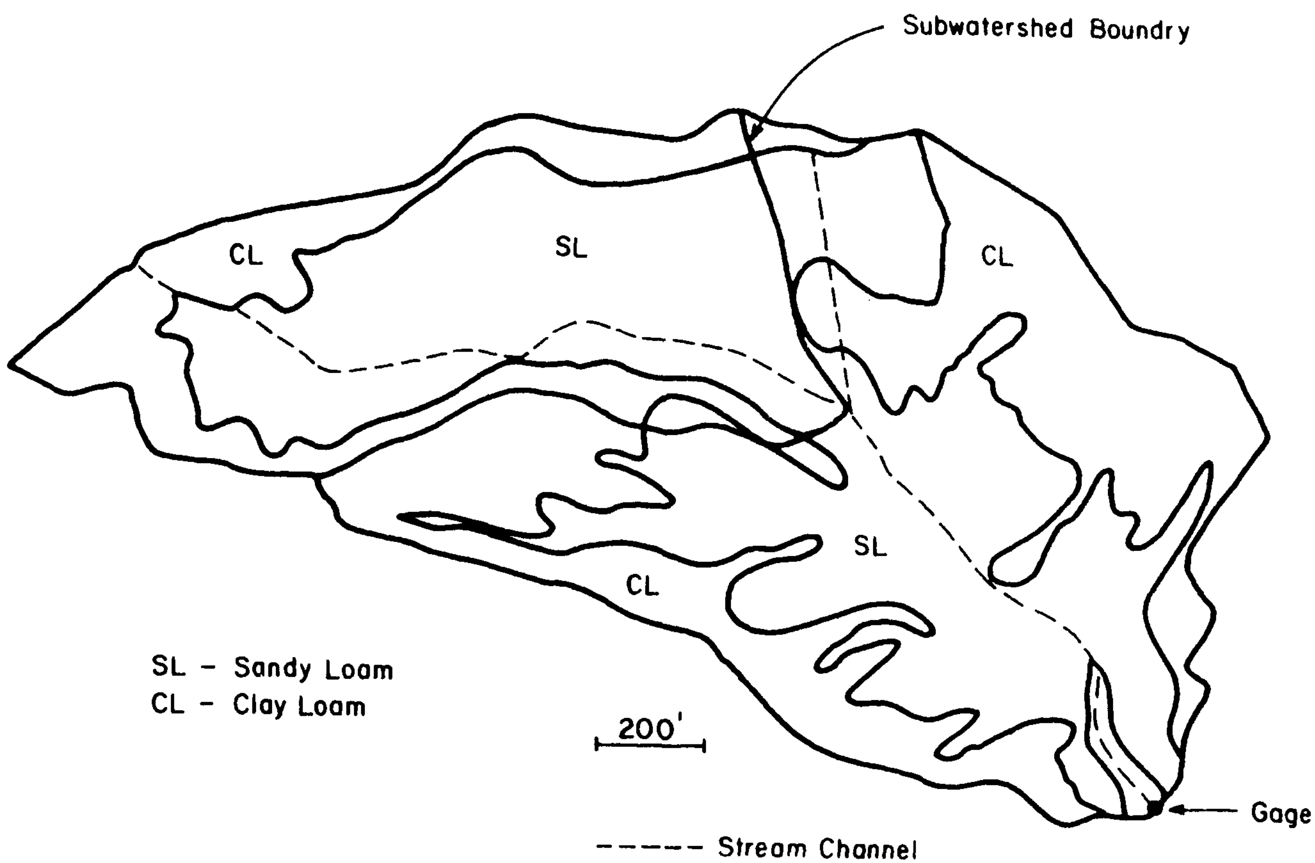

Figure 11. Soils map of Albuquerque ARS Watershed II.

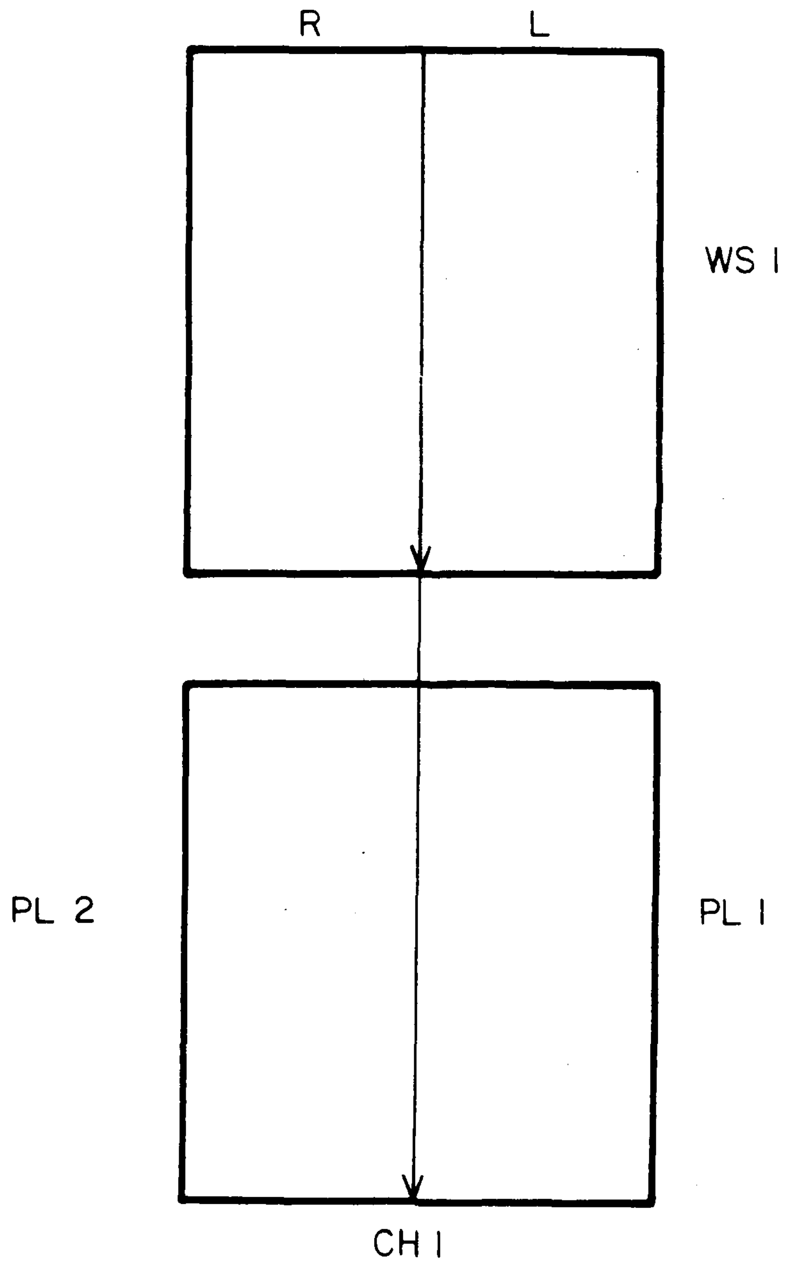

Figure 12. Schematic of Albuquerque ARS Watershed II.

Table 15

Geometric Characteristics

Characteristic	WS1-L*	WS1-R	WS1-CH	PL1	PL2	CH1
Area, acres	8.8	5.7	---	13.3	12.7	---
Length, feet	271	176	1412	583	557	993
Slope, decimal	0.084	0.124	0.072	0.074	0.089	0.040
a1	---	---	6.35	---	---	7.06
a2	---	---	6.32	---	---	7.04

*WS1-L = Watershed 1, left side (looking downstream); WS1-R = Watershed 1, right side; WS1-CH = Watershed 1, channel; PL1 = Plane 1, left side of channel; PL2 = Plane 2, right side of channel; CH1 = Channel 1.

Erosion/Sediment Characteristics

Sand-silt-clay percentages from Table 4 were weighted then plotted on logrithmic grain size-arithmetic probability paper (Figure 13 is the worksheet). Grain size distributions were similar for all watershed segments. The distribution for the planes in the simulation was used throughout because the planes are closer to the watershed outlet. The results of these computations for the soil characteristics are presented in Table 16.

The values COHM = 0.000012 and DCOEFF = 0.001 were assumed. The watershed is usually dry, so a water content of 7 percent was used to calculate initial saturation, SI.

Surface Characteristics

Ground cover for the watershed was reported at about 20 percent with essentially no canopy cover. Potential ground cover interception was estimated at 0.01 in. Impervious area and depression storage were assumed to be zero. Manning's n value for the channel was set at 0.035. The maximum overland flow roughness coefficient was estimated from the USLE K value and Equation 10. Note that ADW must be computed for the entire subwatershed and not each segment. The resultant weighted K values and the computed ADW values are listed below.

Characteristic	WS1	PL1 and PL2
USLE K	0.22	0.21
ADW	13137	13603

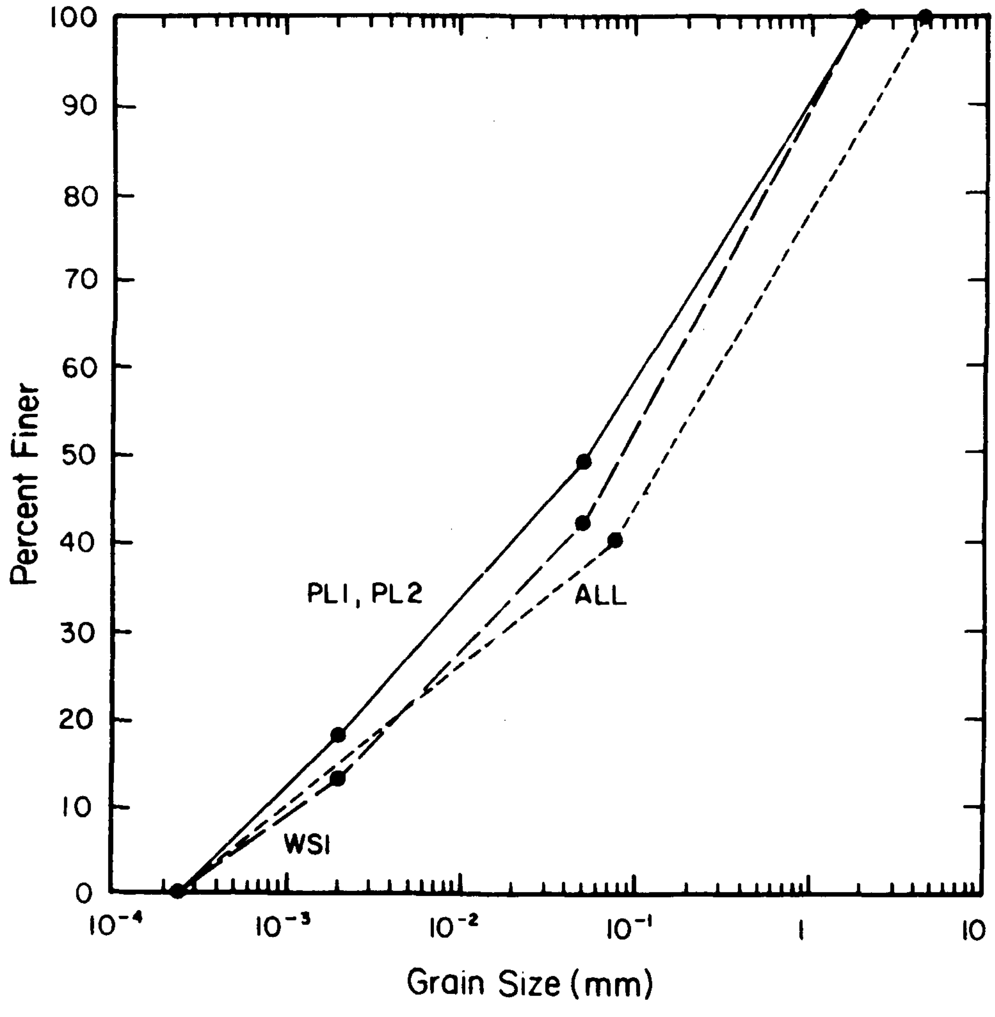

Figure 13. Worksheet for plotting sediment grain size.

Table 16

Computation of Soil Characteristics*

Characteristic	WS1-L	WS1-R	PL1	PL2
Sandy loam, %	72.7	52.6	47.2	50.1
Clay loam, %	27.3	47.4	52.8	49.9
WETK, in./hr	0.63	0.55	**	**
SAVE or SUC, in.	5.4	6.2	**	**
POROS	0.45	0.45	**	**
SW	1.0	1.0	**	**
SI	0.23	0.23	**	**
P or Pf for D				
12.7 mm	100	***	***	***
4.0 mm	100	***	***	***
2.0 mm	100	***	***	***
0.5 mm	81	***	***	***
0.25 mm	71	***	***	***
0.125 mm	62	***	***	***
0.074 mm	55	***	***	***
0.02 mm	40	***	***	***
0.002 mm	18	***	***	***
0.00024 mm	0	***	***	***
DOF	.40	‡	.31	31
PLASI	9	‡	10	10

*A sandy loam soil type was assumed for the channel bed and erosion/sediment characteristics were determined accordingly.

**These are equivalent to the WS1-R values because of the similarity in the soil percentages.

***These are equivalent to the WS1-L values.

‡These are equivalent to the WS1-L values because they must be calculated on the basis of the entire watershed.

Rainfall Characteristics

Two rainfall events were used. The first is the design storm presented in Example 5 for Approach 2. The other storm is a measured event that occurred on June 10, 1966. The characteristics of that storm are listed in Table 17. Total rainfall for this measured event was 1.18 inches in 25 minutes.

Miscellaneous Inputs

The modeled watershed contains one subwatershed, two planes, and one channel. No reservoirs were modeled. Temperature was set at the default value of 70 °F. For the channel, only subwatershed WS1 was contributing from upstream so IWS = 1, 0, 0 and IUP = 0, 0, 0. However, two planes, PL1 and PL2, were contributing so that IPL = 1, 2. DTIM was taken at 1 minute for both events and FTIM was set to 90 minutes for the design event and 55 minutes for the measured event.

Table 17

Rainfall Characteristics

Increment	Ending time, minutes	Intensity, in./hr
1	3	7.60
2	5	1.50
3	7	5.70
4	9	0.30
5	13	6.45
6	16	1.60
7	25	0.27

Measured Storm Simulation

In this simulation, the measured rainfall data were used. Other parameters were the same as in the design storm simulation.

Simulation Using Parameters Derived from Field Data

Information provided by Ward and Bolin[9] was used to determine parameters for the model. Differences were found in soil characteristics when compared to those estimated from Tables 1, 4, and 6. Infiltration and soil erosion measurements at the site provided a different set of values as shown in Table 18. Ground cover was increased to 25 percent as measured in the field. The USLE K factor was found from the nomograph (Figure 9) as 0.22, the same as was estimated previously. All of the other variables remained the same for the simulation. The variable values (Table 18) were computed using area weighted averages. The channel bed is a sandy loam soil. Parameters for the channel were estimated in a manner similar to that described above.

Results

The results for the three sets of information are presented in Table 19. This table shows that the mere selection of a design event will not assure the user that the largest event has been modeled. The data also indicate that, for the measured event, estimating variable values guide provided even better results than when field data were used. This may not be the case for all events, but it demonstrates that using this guide to estimate values can at least provide reasonably realistic answers.

[9] T.J. Ward and S.B. Bolin.

Table 18

Characteristics for the Measured Rainfall Event

Characteristic	WS1-L	WS1-R	PL1	PL2
WETK (in./hr)	1.04	1.02	*	*
SAVE or SUC (in.)	0.42	0.43	*	*
POROS	0.55	0.55	*	*
SW	1.0	1.0	*	*
SI	0.23	0.23	*	*
P or Pf for D				
12.7 mm	100	**	**	**
4.0 mm	98	**	**	**
2.0 mm	88	**	**	**
0.5 mm	68	**	**	**
0.25 mm	58	**	**	**
0.125 mm	48	**	**	**
0.074 mm	40	**	**	**
0.02 mm	31	**	**	**
0.002 mm	15	**	**	**
0.00024 mm	0	**	**	**
DCOEFF***	0.0087	**	**	**
DOF***	.27	**	**	**
PLASI***	8	**	**	**

*Equivalent to the WS1-R values because of similarity the in the soil percentages.
**Equivalent to the WS1-L values.
***Calculated from the clay percentage taken from Figure 13 (15 percent).

Table 19

Simulation Results

Event/Data	Peak Discharge (cfs)	Runoff volume (in.)	Sediment Yield (lb)
Design/no field data	2.15	0.04	3866
Measured/no field data	103.00	0.35	59798
Measured/field data	154.00	0.65	85891
Actual*	77.10	0.39	---

*These are the measured values from the watershed for the event. No sediment yield data were collected.

METRIC CONVERSION TABLE

1 acre	=	0.405 hectare
1 ft	=	0.305 m
1 in.	=	25.4 mm (or 2.54 cm)
1 lb	=	0.453 kg
1 psi	=	703 kg/m^2
1 qt	=	0.95 L
°C	=	0.55 (°F-32)
1 m^2	=	10.76 sq ft
1 mL	=	0.034 oz

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APPENDIX:

RECOMMENDED METHODS FOR FIELD INFILTRATION TESTS

Introduction

Development and use of mathematical models to estimate rainfall, runoff, and associated erosion has made it necessary to collect and analyze field data to derive the needed model parameters. The standard methods for field data collection focus on using a portable rainfall simulator. Because the ARMSED model is based on physical processes, parameters can be derived from field measurements. This model requires parameters related to ground cover, canopy cover, soil properties, infiltration characteristics, erosion coefficients, and hydraulic properties of surface water runoff.

Equipment

Field infiltration studies must be conducted using a blow-down spray-type sprinkling infiltrometer on pairs of 1 meter square (approximately) plots. The following description is provided as an example of the equipment and procedures that will provide the required results.

Methodology

Site Selection

Study sites should be selected to include soil types representing a large percentage of the watershed area. However, not all soil types in the watershed need to be included. Consideration should also be given to soil types in the entire installation. A given soil type may represent a small percentage of soils in the watershed but may make up a larger percentage of soils for the installation. Including the given soil type in this case may save effort in the long run. Approximately 12 plot runs need to be obtained for each soil type.

Field Sampling

The infiltrometer is mounted on a 16-ft trailer. A pair of nozzles is mounted on each of two separate booms, one boom on either side of the trailer. At each parking spot, it is possible to simultaneously simulate rainfall on two plots. These plots are defined using a 1-m^2 square frame made of heavy gage strap steel. This frame is driven into the soil with one side driven flush with the soil surface. That side is where runoff exits the plot, enters a collection trough, and is sampled. This simulator delivers an average rainfall intensity of approximately 4.0 in./hr to the level plot at 2.5 pounds per square inch (psi) inlet pressure to the nozzles. Pressure variations change the intensity of the simulated rainfall. Applied energy to the plot is approximately 60 percent of that expected from natural rainfall. Water is delivered simultaneously to both booms by a pump and water tank mounted on the trailer. First a dry run, then a wet run, are performed as described by the following sequence.

Dry Run

1. Select site and fill in general information on sample sheet (Table A1).

Table A1

Sample Data Sheet

SMALL SIMULATOR DATA SHEET

Project ____ ____________

Plot ID Number ____________ Date ____________ Observer __________

Sunny ____________ Windy ____________ Air Temp. __________

Cloudy ____________ Calm ____________ Water Temp ________

% Vegetation ____________ % Rock Cover ______%

BEFORE RUN — AFTER RUN

Moisture Content Sample

0 - 5 cm ____________ Bed Load Sample ____________

5 - 10 cm ____________ Suspended Sediment Sample ________

Dust Pan Sample ____________ Depth to Wetted Front ____________

(on back)

Rain Gages (on back) ____________

Pan Runoff Times: (seconds) Pan Runoff Times: (seconds)

__________, __________, __________, __________, __________, __________

AFTER WET RUN

Boom Orientation ____________ Soil Sample ____________

(on back)

Slopes (on back) ____________

Clock Time at Start of Rainfall ____________

Table A1 (Cont'd)

All other times measured from start of rainfall (min:sec)

Time of Pan Removal ____________ Time of Pan Replacement ____________

Time to Ponding ____________

Time to Runoff ____________

Time (min:sec)	Runoff Volume (mls)	Time (mis:sec)	Runoff Volume (mls)	Time (min:sec)	Runoff Volume (mls)

Depth of accumulated runoff in collection bucket #

is ____________ inches.

2. Initially position 1-m^2 plot frames.

3. Position trailer carrying rainfall simulator so that booms cover the plots.

4. Install plot frames with trench for collection trough.

5. Seal disturbed soil contacting plot frame with bentonite.

6. Take pictures of the plots and estimate the cover.

7. Connect suction pumps to troughs.

8. Collect soil using a 1-in. interior diameter core sampler to provide moisture and density samples from the top 10 cm of surface on the outside edge of the plot frame. Put in soil cans, label, and seal.

9. Place impervious rainfall collection cover on plot.

10. Install a raingage at each corner of the plot.

11. Install wind screens as needed.

12. Begin simulated rainfall.

13. Sample the rainfall rate using runoff from impervious cover.

14. Remove the impervious cover.

15. Note the times of ponding and runoff into the trough.

16. Pump troughs as necessary (every 3 to 5 minutes).

17. Record pumped volume and accumulate in barrel.

18. Simulate rainfall for approximately 20 to 45 minutes (depending on soil conditions) to assure a steady state runoff.

19. Replace rainfall collection cover and again sample rainfall rate.

20. Stop rain and dump trough a final time.

21. Measure depths of accumulated runoff in barrels.

22. Agitate the barrels and sample 500 ml of water and sediment. Preserve with 10 ml of chlorine bleach in a 1-qt glass jar. Label and seal.

23. Remove deposited material (bed load) from the runoff trough and the runoff tray (metal flume between plot and trough). Bag material in plastic zip-loc bags and label.

24. Record raingage depths in inches and millimeters.

25. Measure depth to wetted front on outside edge of plot.

26. Cover plot with plastic sheet, plywood, and dirt until wet run.

Wet Run (12 to 24 hours later)

27. Repeat steps 6 to 25 above except simulate rainfall for a minimum of 20 minutes or until steady runoff is observed.

28. Measure land slope in the plot with a 2-in. by 4-in. board and a Brunton compass.

29. Remove about 2 lb of soil for sieve analyses from the center of the plot. Save in zip-loc bag.

Sample Containers

Samples of water, sediment, and soil are sent to the laboratory with the sample sheets. Soil moisture cans should be labeled with adhesive tape marked with permanent ink. This tape and ink combination does not fade or burn out when dried in an oven. Plastic bags containing bed load or bulk soil samples should be labeled with masking tape and permanent ink. Runoff water containers should be wrapped with masking tape, so the label will not fall off, and marked with permanent ink.

Each sample container should be prepared prior to the simulations. An information code should be used to distinguish samples from different plots. For example, MiB - Dl would represent samples taken from Minnequa-Wiley Silt Loams (MiB) during the dry run on plot 1 (D1), which is on the driver's side or left of the trailer.

Samples should be boxed and transported to the laboratory at the end of the simulations. At the laboratory, labels should be checked against data sheets. Samples for each item should be verified and inventoried in the data log using the code from the data sheet. This inventory should be permanently affixed to the data log.

Laboratory Measurements

At the laboratory, field samples will be measured and analyzed for several basic data including:

- rainfall depth and duration
- total runoff
- suspended sediment yield
- bed load sediment yield
- final infiltration rate
- saturated hydraulic conductivity
- average capillary suction
- soil moisture and porosity
- depth to wetted front
- soil particle size distribution

- percent of surface cover
- erosion parameters.

Suspended sediment will be filtered following procedures for fine sediments as discussed in the *National Handbook of Recommended Methods for Water-data Acquisition*.[10] The bed load will be air dried and weighed. Cover will be estimated in the field and verified from photographs. Soil moisture will be measured according to USGS (1977). Soil gradation will be determined on a split sample following ASTM specifications D421-58 and D422-63. Bulk density will be found from oven dried weights of core samples. Rainfall rates will be determined by runoff from the impervious cover and verified by the rain gage readings. Runoff will be determined from the measured pumping values and verified by the volume of runoff in the collection barrels. Infiltration and erosion parameters will be derived from the measured and the processed data as discussed in the following section.

Derivation of Parameters

The runoff-erosion process is modeled through interaction of the various definable hydrologic and hydraulic components. Some components are described using semiempirical equations, requiring various coefficients based upon soil characteristics within the watershed.

Specifically, four parameters are of importance. Infiltration is modeled using the relation of Green and Ampt. This relation involves two soil parameters, the saturated hydraulic conductivity (Kw) and the average capillary suction pressure head at the wetting front (Hc). Two other parameters describe sediment supply; one by the mechanism of raindrop detachment (A), and the other by overland flow detachment (DOF). These four parameters, along with other easily measured watershed characteristics, constitute the information necessary to model the runoff-erosion process.

Infiltration Parameters. The Green-Ampt relation for infiltration is of the form:

$$f = \frac{dF}{dt} = Kw\ (1 + \frac{Hc}{F}) \qquad \text{[Eq A1]}$$

where f = instantaneous infiltration rate
t = time
F = accumulated depth of infiltration
Kw = saturated hydraulic conductivity
Hc = Potential head parameter, further described as:

$$Hc = (S_f - S_i)\ nYc \qquad \text{[Eq A2]}$$

where: n = soil porosity
Yc = capillary suction
S_i, S_f = initial and final degree of saturation.

[10] Office of Water Data Coordination, Geological Survey, *National Handbook of Recommended Methods for Water-data Acquisition* (U.S. Department of the Interior, 1977).

The parameters Kw and Hc may be evaluated from a plot of infiltration rate, dF/dt, versus the inverse of the accumulated infiltration depth, 1/F. According to the Green-Ampt relation, this plot must have an intercept on the ordinate of Kw, and a slope equal to (Hc)(Kw). From Hc, Yc may be evaluated using Equation A2.

Accumulated infiltration (F) on the sample plot was obtained as accumulated rainfall less the accumulated runoff. The rain intensity was maintained at a constant value, while the runoff hydrograph was measured incrementally. Thus, F is obtained in increments; F divided by the time increment over which it was collected, provides an estimate for the infiltration rate:

$$f \approx \frac{F}{t} \tag{Eq A3}$$

A linear equation was fitted to the f vs 1/F data calculated for each sample plot using a "least squares" technique. Interpretation of the resulting parameters was governed by the reality of the infiltration process, and aided by statistical inferences available within the least squares technique. If the least squares technique was inadequate, Kw was examined and replaced by the measured final infiltration rate in later computations. The values of Kw and Yc derived in this manner can be thought of as representative parameters for the soil.

Detachment Parameters. The erosion process is characterized by the interaction of the sediment transporting capacity of the overland flow, and the sediment supply. Sediment transport is by two mechanisms, bed load and suspended load. Sediment supply occurs from two mechanisms, raindrop detachment and overland flow detachment. To evaluate the detachment parameters, it was assumed that transporting capacity was in excess, so the measured suspended and bed loads were directly related to the detachment processes. Further, the suspended load was viewed as primarily dependent on the process of raindrop detachment, and the bed load dependent on the process of overland flow.

Raindrop Parameters. This detachment process is modeled to be proportional to the square of the rain intensity or:

$$\text{Sediment Yield Rate} = (A)(I^2) \tag{Eq A4}$$

where A = raindrop detachment coefficient
I = rainfall intensity (in./hr)

The coefficient A can be evaluated for each rain event on each plot, with the assumption that the measured suspended load represented raindrop detachment. Since rain intensity was constant during a rain event, A is calculated as the ratio of suspended sediment to I, after adjusting this measured sediment for the deficient energy of the simulated rainfall.

Kinetic energy of natural rainfall is assumed to be related to the rain intensity:

$$KE = 916 + 331 \text{ LOG}_{10} (I) \tag{Eq A5}$$

where KE = rainfall energy $\frac{\text{ft-tons}}{\text{acre-inch}}$

This relation is difficult to reproduce using simulated rainfall; a simulated rainfall of a certain intensity will typically have an energy below that of natural rainfall. A consequence of this reduced energy is a decrease in sediment supply from raindrop detachment; the measured suspended load should be lower than that observed under natural rainfall. To adjust A for this reduced energy, the measured suspended load can be increased by multiplication with the ratio of natural rainfall energy to the simulated rainfall energy. Coefficient A is calculated based on bare unprotected surface area.

Overland Flow Detachment. The model used for this process is that common to the physical process models developed at Colorado State University. In these models, overland flow detachment is a fraction of excess sediment transport capacity. The parameter describing this process represents the ratio of overland flow detachment to the excess sediment transport capacity. Excess sediment transport capacity exists when transport capacity exceeds that necessary to transport sediment supply created by raindrop detachment. In equation form:

$$\text{overland flow} = \text{DOF}\ \frac{(\text{transport capacity} - \text{raindrop supply})}{\text{sediment supply}} \qquad \text{[Eq A6]}$$

where DOF = overland flow detachment coefficient.

Measured bed load can be used to represent the overland flow sediment supply, and the energy-adjusted measured suspended yield can be equated to the raindrop sediment supply. Transport capacity can be calculated as the sum of the bed load and suspended load capacities calculated from measured plot and soil characteristics. Bed load capacity was determined from the Meyer-Peter-Muller bed load relation and suspended load capacity was predicted using Einstein's equation.

Sources of Error

As in any field experiments, error is possible due to onsite conditions not being optimum. Two conditions can often affect results to some extent. One condition can occur on gentle slopes where ponded water has caused a lag in runoff response and extra soil protection from raindrop splash. These are natural occurrences and are thus representative of site conditions, although they may have some effect on the derivation and comparison of parameters. The second condition is wind, which can be intermittent and multidirectional. Because of this, almost all runs can exhibit wind effects, but fortunately, few are affected enough to preclude use of the rainfall data.

Results

Include a figure showing locations of watershed sampling sites in the report. Figure A1 is an example. Table A2 is an example presentation of the soil codes and descriptions for mapped units in a watershed. Table A3 is an example of the number of plots sampled for each soil type. Table A1 shows a data collection sheet.

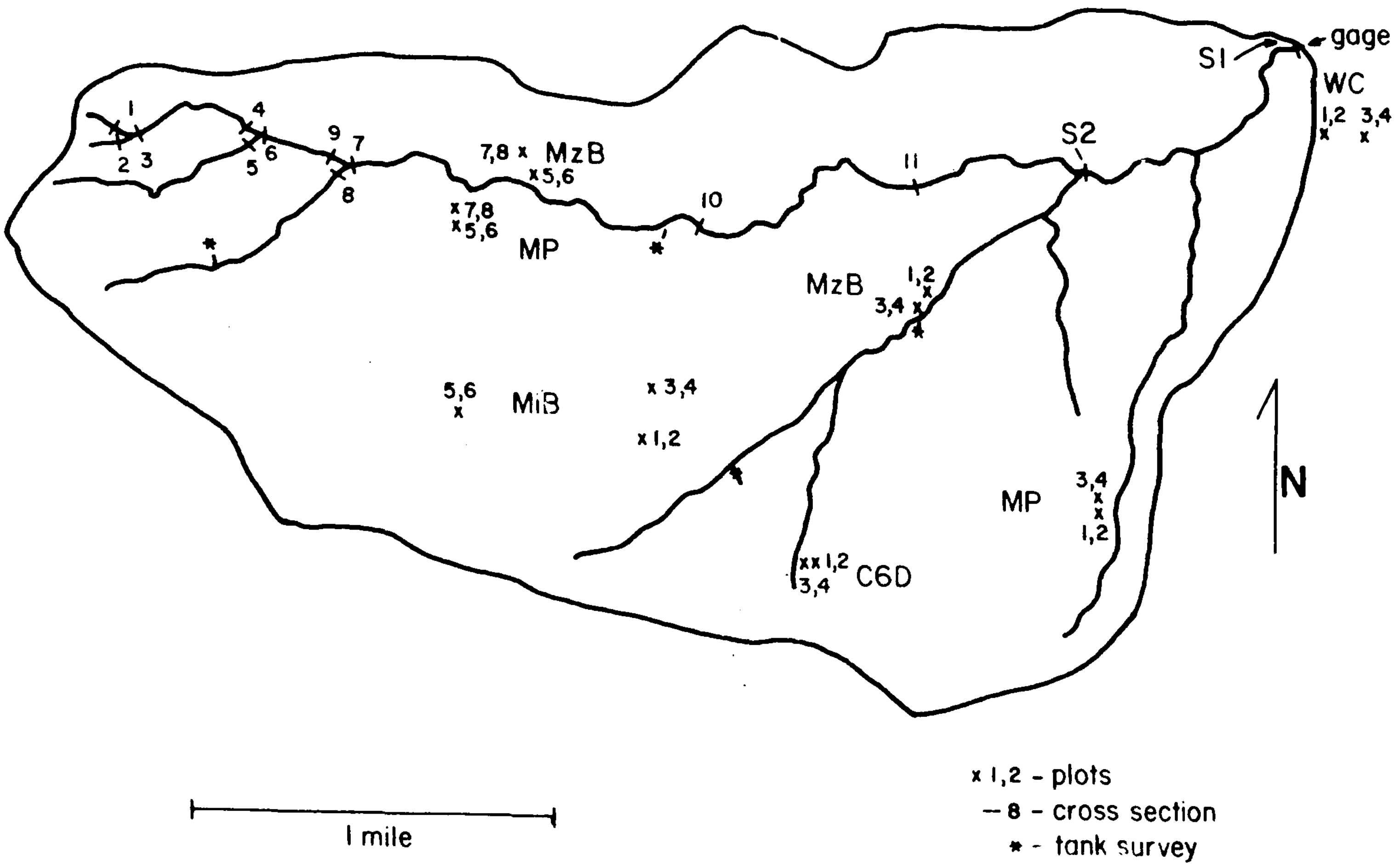

Figure A1. Watershed sampling sites.

Table A2

Soil Codes and Description for Mapped Units in the Pinon Canyon Experimental Watershed

Map Symbol	Percent of Watershed	Description (percent slope)
C6D	8	Cadoma Clay (4 to 6)
MiB	15	Minnequa-Wiley Silt Loams (1 to 6)
MP	35	Midway-Gaynor Complex, gravelly and silty clay loams
MzA	1	Manzanola Silty Clay Loam (0 to 1)
MzB	25	Manzanola Silty Clay Loam (1 to 4)
SaD	5	Midway Clay Loam (3 to 15, gullied)
ShD	3	Shingle-Penrose Complex (2 to 15)
TsD	3	Travessilla-Rock Outcrop Complex (25 to 65)
WiB	2	Wiley Loam (0 to 3)
WC	3	Wiley-Villegreen Loams (1 to 4)

Table A3

Soils Sampled for Infiltration and Sediment Yields

Soil Symbol	Number of Plots*
C6D	4
MiB	6
MP	8
MzB	8
WC	4

*Each plot subjected to dry and wet runs.

Summaries and statistics of the data should also be presented. Important plot or site characteristics include antecedent soil moisture on a dry weight basis, overland slope, soil porosity, rock cover on the soil surface, vegetative cover on the soil surface, and soil gradation. Table A4 is an example of how these data should be presented. Observations on differences between soil plots should be made in the text discussion. An analysis of variance (ANOVA) F-test should be made to identify differences among properties of the soils.

Rainfall and runoff should be described. Include the length of runs, wind effects, rainfall rates, and the ratio of runoff to rainfall. Use the ANOVA test to identify variations of rainfall rate with different soils. Differences between wet and dry runs should be noted and explained. Table A5 is an example presentation of rainfall-runoff information.

Infiltration, erosion, and sediment yield should be divided into measured values and derived parameters. The final infiltration rate may be the average of the final three time points from the rainfall-runoff data, excluding the last pumped sample. Other data includes depth in the soil to the saturated front and sediment yields for suspended, bed, and total (sum of suspended and bed loads) loads. The total yield should be presented as tons of soil per acre-in. of runoff in order to normalize for runoff. Table A6 is an example presentation of measured infiltration and erosion values. Figure A2 shows the estimation of Green-Ampt infiltration parameters from field data. Differences between dry and wet runs should be discussed and an ANOVA test should be made to determine soil response to suspended sediment yield.

Infiltration and erosion parameters should be derived using the procedures previously described. Where appropriate, the final infiltration rate can be used in lieu of Kw, and capillary suction can be computed on that basis. Table A7 is an example presentation of derived parameters. ANOVA test should be used to identify differences in the raindrop splash detachment coefficient and the overland flow detachment coefficient among soils for wet and dry runs.

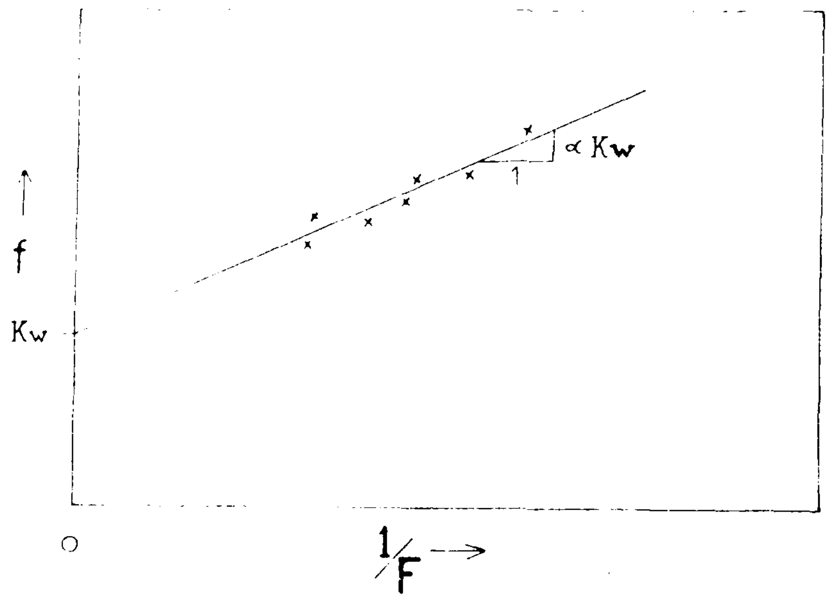

Figure A2. Estimation of green-ampt infiltration parameters from field data.

Table A4

Statistics for Plot Characteristics

Characeristic, in percent*	C6D Mean	C6D S.D.	MiB Mean	MiB S.D.	MP Mean	MP S.D.	MzB Mean	MzB S.D.	WC Mean	WC S.D.
Dry Run Antecedent Moisture	9.25	1.51	3.5	2.41	6.9	3.5	12.4	2.61	5.5	1.0
Wet Run Antecedent Moisture	19.0	3.7	23.2	4.5	22.6	3.2	23.9	3.4	23.5	0.6
Slope	4.8	2.1	3.6	1.0	7.0	3.5	4.2	1.8	4.8	1.7
Porosity	51.0	2.2	58.5	5.1	59.2	3.8	57.5	3.3	55.8	2.2
Rock Cover	56.8	30.3	0.0	0.0	29.5	22.5	1.2	1.3	0.0	0.0
Vegetation Cover	25.2	16.8	54.4	16.0	39.4	8.8	58.0	18.5	49.7	20.4
Gravel	9.5	3.3	0.5	0.8	12.0	4.3	1.9	1.8	3.8	4.1
Sand	28.3	9.9	22.0	11.8	16.8	6.3	20.4	5.7	21.8	9.7
Fines	62.2	13.3	77.5	11.8	71.2	6.1	77.7	5.0	74.4	14.0

*All characteristics except antecedent moisture were the same for dry and wet runs.

Table A5

Statistics for Rainfall and Runoff

	C6D				MiB				MP			
	Dry		Wet		Dry		Wet		Dry		Wet	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Rainfall Rate, in./hr	4.01	0.13	4.24	0.13	4.43	.23	4.56	0.29	3.95	0.43	3.98	0.39
Rainfall Depth, in.	1.34	0.05	1.41	0.04	1.48	0.06	0.80	0.98	1.42	0.18	1.37	0.19
Runoff Depth, in.	0.68	0.25	1.11	0.16	0.49	0.33	1.54	0.14	0.64	0.19	0.84	0.17
Runoff/ Rainfall	0.51	0.18	0.78	0.10	0.40	0.23	0.51	0.17	0.46	0.14	0.61	0.09

Table A5 (Cont'd)

	MzB				WC			
	Dry		Wet		Dry		Wet	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Rainfall Rate, in./hr	3.93	0.90	3.86	0.44	4.38	0.21	4.70	0.24
Rainfall Depth, in.	1.31	0.03	1.28	0.15	1.46	0.07	1.56	0.08
Runoff Depth, in.	0.51	0.22	0.84	0.13	0.74	0.24	1.04	0.26
Runoff/ Rainfall	0.39	0.17	0.66	0.10	0.51	0.18	0.66	0.15

Table A6

Measured Infiltration and Sediment Yield Values

	C6D				MiB				MP			
	Dry		Wet		Dry		Wet		Dry		Wet	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Final Infiltration Rate, in./hr	1.19	0.85	0.50	0.18	2.13	1.09	1.52	0.54	1.66	0.54	1.05	0.36
Suspended Load Yield, grams	4.41	49.8	48.9	37.1	18.7	21.9	13.9	13.4	29.7	20.1	17.1	9.3
Bed Load Yield, grams	25.7	21.5	24.0	14.9	11.6	11.8	4.5	5.8	23.0	8.5	7.2	3.9
Total Sediment Yield, T/AC-in	0.41	0.28	0.29	0.16	0.29	0.16	0.10	0.06	0.37	0.11	0.13	0.05

Table A6 (Cont'd)

	MzB				WC			
	Dry		Wet		Dry		Wet	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Final Infiltration Rate	1.87	0.75	0.86	0.49	1.56	0.88	1.09	0.51
Suspended Load Yield, grams	24.1	17.7	24.6	8.3	37.8	28.0	34.9	15.5
Bed Load Yield, Grams	22.0	23.6	13.5	13.1	22.0	18.6	18.8	23.3
Total Sediment Yield T/AC. -in	0.38	0.18	0.21	0.09	0.35	0.20	0.24	0.12

Table A7

Derived Infiltration and Erosion Parameters

	C6D				MiB				MP			
	Dry		Wet		Dry		Wet		Dry		Wet	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Representative Hydraulic Conductivity in./hr	1.19	0.85	0.50	0.18	1.52	0.92	1.21	0.48	1.22	0.74	0.94	0.22
Representative Capillary Suction, in.	1.34	1.01	4.08	4.93	0.92	0.87	2.04	1.94	1.76	1.93	1.36	1.05
Raindrop Splash Detachment Coefficient	.01318	.01577	.01757	.02623	.00047	.00039	.02433	.02692	.00170	.00172	.00092	.00059
Overlend Flow Detachment Coefficient	0.012	0.010	0.009	0.010	0.005	0.003	0.001	0.0004	0.005	0.002	0.001	0.001

Table 7 (Cont'd)

	MzB				WC			
	Dry		Wet		Dry		Wet	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Representative Hydraulic Conductivity, in./hr	1.30	0.68	0.74	0.31	1.56	0.88	0.84	0.68
Representative Capillary Suction, in.	2.03	2.06	2.22	2.07	0.74	0.87	1.52	1.26
Raindrop Splash Detachment Coefficient	.00080	.00050	.00090	.00030	.00067	.00038	.00060	.00012
Overland Flow Detachment Coefficient	0.009	0.013	0.003	0.004	0.004	0.003	0.002	0.002

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